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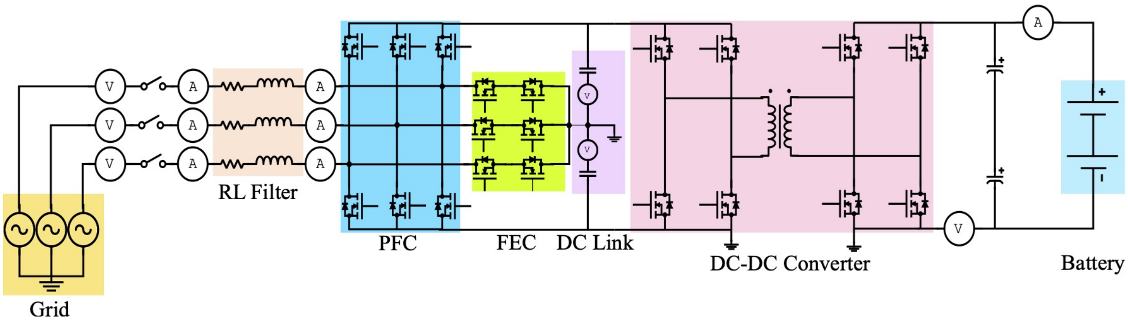

Second Life for Commercial Vehicles On-board Charging Electrical Power System

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Circuit Diagram of an On Board Charger with Isolation.

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Abstract

The study begins by analyzing market studies to gauge the demand for repurposed OCEPS and this evaluation aims to determine the market's readiness for such a transition. Moreover, the research conducts a thorough examination of existing OCEPS designs and their limitations. This analysis is crucial for proposing improvements that enhance overall efficiency, calculate losses accurately, and optimize performance. The intention is to ensure that repurposed DC chargers not only match technical requirements but also surpass previous models in energy efficiency and reliability.

The study begins by examining the state of onboard charger technology highlighting its crucial role in EV performance and the challenges it poses in terms of environmental impact and economic sustainability. Recognizing that onboard chargers often outlast the vehicle this investigation explores the potential for repurposing or reusing these chargers for purposes thereby contributing to a more circular and sustainable economy. A significant contribution of this study is the development of a sustainable business model tailored to the repurposing process. This model seeks to combine economic feasibility with circular economy principles by leveraging market opportunities and addressing environmental concerns through efficient resource utilization and waste reduction. It then delves into the evaluation of current designs and the suggested improvements, highlighting potential enhancements in technical efficiency. Lastly, the discourse revolves around the innovative sustainable business model, which harmonizes economic viability and ecological responsibility.

The research findings not only reveal the potential of onboard chargers but also propose a systematic framework for identifying and implementing second life opportunities, within the electric mobility ecosystem. The study's implications go beyond the concerns of EV technology. Provide insights, into broader sustainability practices and the circular economy. If stakeholders, in the electric vehicle industry embrace the idea of giving onboard chargers a life they can contribute to a sustainable future while tackling the challenges posed by electronic waste. In summary, this thesis explores the conversion of OCEPS into DC chargers through a circular economy lens. By evaluating market demand, improving designs, and proposing a sustainable business model, the study bridges technological advancement and sustainability, fostering economic growth while respecting environmental balance.

Keywords: Circular Economy, Sustainability, Economic Feasibility, Waste Reduction, Power Electronics

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Ajay Krishna Voppu Muralikrishna and Viswanathan Ganesh, Gothenburg, September 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
BOBC	Bidirectional On Board Charger
CAN	Controlled Area Network
DAB	Dual Active Bridge
DC	Direct Current
DIN	Direct Current
EV	Electric Vehicle
EOL	End of Life
FEC	Front End Converter
FFT	Fast Fourier Transformation
G2V	Grid to Vehicle
IP	Internet Protocol
LCA	Life Cycle Analysis
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MTTF	Mean Time To Failure
NVH	Noise Vibration and Harshness
OCEPS	On-board Charging Electric Power Systems
PFC	Power Factor Correction
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
SPS	Single Phase Shift
SiC	Silicon Carbide
TCP	Transmission Control Protocol
THD	Total Harmonic Distortion
V2H	Vehicle to Grid
V2H	Vehicle to Home
V2L	Vehicle to Load
V2X	Vehicle to Everything
ZVS	Zero Voltage Switching

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1
Introduction

1.1 Background

As the automotive sector shifts towards electrification, there has been a notable rise in the presence of electric vehicles (EVs) within the market in recent times [1]. Consequently, the establishment of an ample and easily accessible charging infrastructure within society becomes imperative to facilitate the recharging of EV batteries and alleviate driver concerns about limited range. In tandem, vehicle batteries have also grown in size to enhance the distance these vehicles can travel, resulting in a corresponding increase in the overall weight of the vehicles [2].

The Electromobility Division within VOLVO GTT (Group Truck Technology) holds the responsibility for advancing forthcoming energy transmission technologies for the VOLVO AB Group. This division is also tasked with the innovation of electric propulsion systems, encompassing all components operating at high voltage. Within this unit, the OCEPS department is actively engaged in exploring and identifying potential second-life applications and viable business opportunities for the current OCEPS modules utilized in their electric commercial trucks.

The assignment is to calculate the lifetime of the existing OCEPS and explore the possibility of repurposing it into an Off Board DC charger by comparing it with existing market competition and have an economically viable scaling-up solution that can be profitable both for the company and beneficial for the environment with respect to circular economy and reduction in e-waste generation.

One benefit of having the concept of circular economy is to reduce the waste generation and since the existing truck was used in the EV truck it would have all necessary certifications both in terms of regulation and NVH certifications.

1.2 Aim

The aim of this thesis is to develop a second life application based on lifetime calculations and re-purpose the existing OCEPS into a market-viable Off Board charger which can be both profitable to the company and environmentally beneficial in terms of reduction in e-waste and sustainability.

1.3 Objectives

In order to explore the second life application of an OCEPS, the following objectives will be investigated:

- An extensive literature survey of existing topologies to match our product
- The electrical performance of the existing product will be considered and simulated. Theoretical calculations will be performed to check the difference in the circuit parameters
- Update circuit parameters and simulate to verify THD and proper working
- Simulate the thermal Model of SiC power modules and calculate temperature and efficiency of the same and perform lifetime calculations for the power modules.
- Evaluate the limitations and challenges associated with repurposing on-board charging systems, including technical constraints, safety considerations, and regulatory requirements, and contribute to the existing knowledge on sustainable transportation.
- Explore possibilities of potential applications such as grid-scale energy storage, vehicle-to-home (V2H) and vehicle-to-grid (V2L) systems, off-grid applications, and renewable energy integration.
- Based on the circular economy shortlist components that can be repurposed and proceed with the mechanical design of the proposed product (CAD model)
- Analyse market competitions and develop a business case scenario

1.4 Problem

The primary issue with an AC/DC converter relates to its non-linear load. These loads tend to inject undesirable frequency in the parameter of current hence increasing the Total Harmonic Distortion(THD), which in turn leads to poor quality of power delivery. Having a higher switching frequency generates electronic noises there is a requirement to reduce the electromagnetic interference using a well-calculated filter. The existing filter had issues pertaining to harmonic distortions and noise due to incorrect filter parameters.

A concealed box housing semiconductors supplying a higher load in terms of kilowatts tends to consume higher currents. The losses in a resistive load system are proportional to the square of current flowing in the circuit. These losses are referred to as thermal losses which tend to increase the temperature of silicon devices and hamper their performances. Hence a proper cooling system is required to maintain the temperature of the components under the maximum limit.

The process of re-purposing the device comes with an issue of understanding individual components and calculating its lifetime to ensure the continuous working of the module as expected. The repurposed components must be easily replaceable and accessible. If required we need to add additional components to enhance its application and make it as redundant possible to ensure the product is flexible to adapt itself to multiple applications.

The product is expected to be compact and lightweight compared to the competitors. It must be easily expandable in terms of higher capacities. It must abide by all rules and regulations to be allowed to be a product in the market. It has to be competitively priced and must be better than the competitor's product.

1.5 Thesis Structure

The scope of this project encompasses a comprehensive study and development of a Second Life Onboard Charging Electrical Power System for commercial vehicles, with a strong emphasis on repurposing components, evaluating performance, addressing technical challenges, and contributing to sustainable transportation. The project will be executed through the following key stages:

Literature Survey: Conduct an extensive literature review to identify and analyze existing topologies of onboard charging electrical power systems for commercial vehicles. Evaluate their design principles, operational efficiency, and compatibility with repurposing.

Electrical Performance Evaluation: Assess the electrical performance of the existing onboard charging power system through simulations and practical testing. Measure and compare key parameters such as voltage regulation, current handling capacity, power efficiency, and harmonic distortions.

Theoretical Calculations: Perform theoretical calculations to determine the differences in circuit parameters, including power losses, voltage drops, and current ratings, between the existing system and the proposed Second Life system. Analyze the impact of these differences on system efficiency and overall performance.

Thermal Modeling and Analysis: Develop a thermal model for the Silicon Carbide (SiC) power modules used in the onboard charging system. Simulate the thermal behavior, calculate operating temperatures, and estimate efficiency. Perform lifetime calculations to predict the longevity of the power modules under different operating conditions.

Challenges and Limitations: Identify and evaluate technical constraints, safety considerations, and regulatory requirements associated with repurposing onboard charging systems for commercial vehicles. Analyze challenges related to hardware compatibility, integration, and performance optimization.

Sustainable Transportation: Contribute to the existing knowledge on sustainable transportation by highlighting the advantages of repurposing and extending the lifecycle of onboard charging systems. Explore circular economy principles and identify components suitable for repurposing. Emphasize the environmental benefits of reducing waste and promoting resource efficiency.

Additional Components: Selection of additional components required for the smooth operation of the repurposed product in terms of communication, cooling apparatus, and structural changes.

Mechanical Design (CAD): Based on circular economy principles, shortlist components that can be repurposed and integrated into the onboard charging system. Develop a mechanical design using Computer-Aided Design (CAD) software, ensuring compatibility, fit, and proper thermal management.

Market Analysis and Business Case: Analyze the current market landscape for commercial vehicle onboard charging systems. Identify key competitors, market trends, and potential customer segments. Develop a comprehensive business case scenario that outlines the economic feasibility, potential revenue streams, and cost effectiveness of the proposed Second Life system.

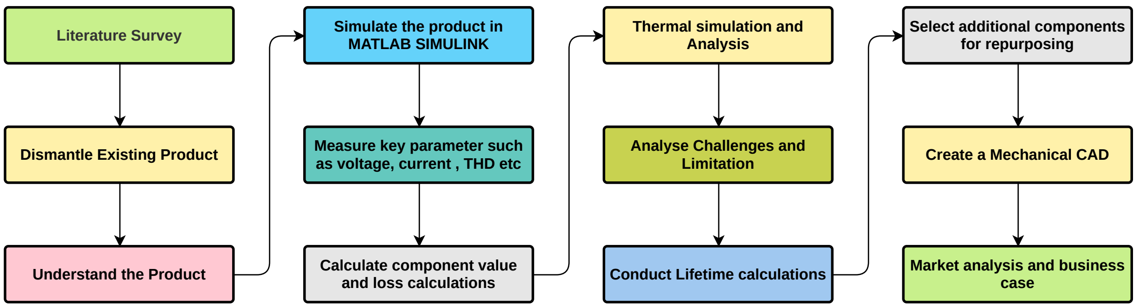


Figure 1.1: Method Flowchart

In summary, this project aims to explore, evaluate, and enhance the feasibility of repurposing onboard charging systems for commercial vehicles. By conducting a thorough literature survey, assessing electrical and thermal performance, addressing technical challenges, and contributing to sustainable transportation principles, the project seeks to develop a viable and environmentally responsible solution while considering economic viability in the market.

2
Literature Review

The literature review chapter provides a comprehensive overview of existing research and scholarly work related to second-life applications for onboard charging electric power systems in electric vehicles (EVs). This chapter serves as the foundation for the research, offering a theoretical framework and identifying gaps in the current knowledge. The review covers various aspects, including onboard charging systems, second-life applications, and the environmental and economic implications of repurposing EV components.

2.1 Overview of OnBoard Charging Electric Power Systems

The article titled "Simulation and testing of a typical on-board charger for ITB electric vehicle prototype application" was published in the journal Procedia Technology in 2013. The authors of the article are A. Purwadi, J. Dozeno, and N. Heryana. [**2**] The study focuses on the simulation and testing of an on-board charger for an electric vehicle (EV) prototype developed by ITB (Institut Teknologi Bandung). The on-board charger is an important component of an EV that allows it to charge its battery from an external power source.

The authors describe the process of simulating and testing the on-board charger to evaluate its performance and functionality. They discuss the various components and subsystems of the charger, such as the AC-DC converter, DC-DC converter, and the charging algorithm.

The simulation phase involves using computer software to model and analyze the charger's behavior under different operating conditions. The authors examine factors such as efficiency, power factor, and harmonic distortion to assess the charger's performance.

In the testing phase, the authors validate the simulation results by conducting physical tests on the on-board charger. They measure and analyze parameters such as voltage, current, and power characteristics during the charging process. The testing helps to verify the charger's performance in real-world conditions and compare it with the simulation results.

The article presents the simulation and testing results, discussing the performance and efficiency of the on-board charger. The authors also highlight the challenges and potential improvements for future development and optimization of the charger for EV applications.

Overall, the article provides insights into the simulation and testing process of an on-board charger for an electric vehicle prototype. It contributes to the understanding of the performance and functionality of on-board charging systems and informs the development of more efficient and reliable charging solutions for electric vehicles.

The article titled "A critical review on charging technologies of electric vehicles" was published in the journal Energies in 2022. The authors of the article are M. Shahjalal, T. Shams, M. N. Tasnim, M. R. Ahmed, M. Ahsan, and J. Haider.[**9**]

The study provides a critical review of charging technologies for electric vehicles (EVs). The authors examine the different charging methods and technologies available for charging EVs, with a focus on their advantages, limitations, and future prospects.

The article begins by discussing the importance of charging technologies in supporting the widespread adoption of EVs. The authors highlight the need for efficient, reliable, and convenient charging solutions to address the range anxiety and charging infrastructure limitations often associated with EVs.

The study covers various charging technologies, including slow charging, fast charging, wireless charging, and ultra-fast charging. The authors analyze the characteristics, charging rates, and compatibility of each technology with different EV models. They discuss the infrastructure requirements, cost implications, and user experiences associated with each charging method.

Furthermore, the article explores the challenges and limitations of existing charging technologies. The authors address issues such as charging time, grid integration, power quality, standardization, and interoperability. They also discuss the impact of charging technologies on the overall energy system, considering factors such as peak demand, load management, and renewable energy integration.

The study provides a critical assessment of the current state of charging technologies and highlights the ongoing research and development efforts in the field. The authors discuss emerging trends and advancements, such as dynamic wireless charging, bidirectional charging, and smart charging algorithms. They also highlight the role of policy frameworks, regulations, and industry collaborations in shaping the future of EV charging technologies.

Overall, the article offers a comprehensive review of charging technologies for electric vehicles. It examines the advantages, limitations, and challenges associated with different charging methods and provides insights into the future direction of

EV charging technology. The study contributes to the understanding of the evolving landscape of EV charging and informs stakeholders about the considerations and developments in this important aspect of electric mobility.

The chapter titled "Modeling of electric vehicle DC fast charger" is part of the book "Electric Transportation Systems in Smart Power Grids." The authors of the chapter are V. Ganesh, V. M. Krishna, S. Senthilmurugan, and S. Hemavathi.[**14**]

The chapter focuses on the modeling of electric vehicle (EV) DC fast chargers, which play a crucial role in enabling rapid charging for EVs. The authors discuss the various aspects of modeling these chargers, including their components, control algorithms, and performance evaluation.

The chapter begins by providing an overview of DC fast charging technology and its importance in facilitating quick charging of EVs. The authors discuss the significance of fast charging in reducing charging time and improving the practicality and convenience of EVs.

The authors then delve into the modeling of DC fast chargers, starting with an examination of the charger's components and their functionalities. They discuss key components such as the power electronic converter, the charging protocol interface, and the communication system. The chapter provides insights into the operation and characteristics of each component, emphasizing their role in efficient charging.

Furthermore, the authors discuss the control algorithms employed in DC fast chargers. They explain the importance of control strategies in ensuring the safe and optimal charging of EVs. The chapter covers various control techniques, including current control, voltage control, and power factor correction, and discusses their implementation and impact on charger performance.

The chapter also addresses the performance evaluation of DC fast chargers. The authors discuss the metrics used to assess the charger's efficiency, power quality, and reliability. They explain the importance of accurate modeling and simulation in understanding the charger's behavior and performance under different operating conditions.

Overall, the chapter provides a comprehensive overview of the modeling of electric vehicle DC fast chargers. It covers the components, control algorithms, and performance evaluation of these chargers. The chapter contributes to the understanding of DC fast charging technology and informs researchers and practitioners about the modeling techniques and considerations involved in designing efficient and reliable charging solutions for electric vehicles.

The article titled "A study on trends and developments in electric vehicle charging technologies" was published in the Journal of Energy Storage in 2022. The authors of the article are S. Hemavathi and A. Shinisha.[**6**]

The study aims to explore the latest trends and developments in electric vehicle (EV) charging technologies. The authors investigate the advancements in charging infrastructure and associated technologies to support the growing adoption of EVs.

The article discusses different types of EV charging technologies, including AC charging, DC charging, wireless charging, and fast charging. The authors examine the characteristics, advantages, and limitations of each technology, considering factors such as charging speed, convenience, and compatibility with different EV models.

Furthermore, the study explores the latest trends in EV charging infrastructure. The authors discuss the deployment of charging stations in various locations, such as homes, workplaces, public spaces, and along highways. They also analyze the integration of charging infrastructure with smart grids and renewable energy sources to enhance the sustainability and efficiency of charging operations.

The article highlights the developments in EV charging technologies, such as vehicle-to-grid (V2G) systems, which allow bidirectional energy flow between EVs and the grid. The authors discuss the potential benefits of V2G systems, including grid stabilization, load management, and revenue generation for EV owners.

Additionally, the authors examine the challenges and future prospects of EV charging technologies. They discuss issues related to standardization, interoperability, charging infrastructure planning, and policy frameworks. The article also highlights the emerging trends in charging technologies, including advancements in battery technologies, autonomous charging, and predictive charging algorithms.

Overall, the article provides insights into the trends and developments in EV charging technologies. It informs readers about the different charging options available, the integration of charging infrastructure with smart grids and renewable energy sources, and the potential benefits and challenges associated with these technologies. The study contributes to the understanding of the evolving landscape of EV charging and informs the development of efficient and sustainable charging solutions.

The article titled "A review of bidirectional on-board chargers for electric vehicles" was published in IEEE Access in 2021. The authors of the article are J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers, and A. Emadi.[**7**]

The study provides a comprehensive review of bidirectional on-board chargers (BOBC) for electric vehicles (EVs). BOBCs are a type of charger that not only enables the vehicle to charge its battery from an external power source but also allows bidirectional power flow, enabling the vehicle to discharge energy back into the grid or other external loads.

The article discusses the importance and potential applications of bidirectional charging in EVs. The authors highlight the benefits of bidirectional charging, such as vehicle-to-grid (V2G) capabilities, peak shaving, grid support, and energy management. They explore the various use cases and potential benefits of BOBCs, including grid resilience, renewable energy integration, and cost savings for EV owners.

The authors provide an overview of the components and functionalities of BOBCs. They discuss the key features of bidirectional chargers, including power electronics, control algorithms, communication interfaces, and safety mechanisms. The article also addresses the challenges associated with BOBCs, such as efficiency, power quality, grid compatibility, and standardization.

Furthermore, the review discusses the recent advancements and developments in BOBC technology. The authors highlight the research efforts and innovations in power electronics, control strategies, and system integration. They explore the emerging trends in BOBC design, such as modular architectures, advanced control algorithms, and integration with renewable energy systems.

Overall, the article provides a comprehensive review of bidirectional on-board chargers for electric vehicles. It covers the concept, applications, components, challenges, and recent developments in BOBC technology. The study contributes to the understanding of the potential of bidirectional charging in the context of EVs and informs researchers and engineers about the latest advancements in BOBC design and implementation.

The article titled "Electric vehicle charging topologies, control schemes for smart city application" was presented at the 2019 IEEE Transportation Electrification Conference (ITEC-India). The author of the article is S. K. Nayak.[**10**]

The study focuses on electric vehicle (EV) charging topologies and control schemes specifically designed for smart city applications. The author explores the various charging topologies and control strategies that can facilitate efficient and sustainable EV charging in the context of smart cities.

The article discusses different EV charging topologies, including centralized charging, decentralized charging, and hybrid charging. The author analyzes the characteristics and advantages of each topology, considering factors such as charging efficiency, power distribution, scalability, and flexibility. The study emphasizes the importance of selecting an appropriate charging topology based on the specific requirements and constraints of smart city environments.

Furthermore, the author addresses the control schemes for managing EV charging in smart cities. The article explores various control strategies, such as load management, peak shaving, demand response, and vehicle-to-grid (V2G) integration. The author discusses the benefits of intelligent control schemes in optimizing charging operations, improving grid stability, and maximizing the utilization of renewable energy sources.

The study highlights the role of smart city applications in EV charging. The author discusses the integration of EV charging infrastructure with smart grids, energy management systems, and communication technologies. The article explores how smart city concepts can enhance the coordination and control of EV charging, enable dynamic pricing mechanisms, and facilitate efficient energy utilization.

Overall, the article provides insights into EV charging topologies and control schemes tailored for smart city applications. It discusses the advantages and considerations of different charging topologies and highlights the potential benefits of intelligent control strategies in optimizing EV charging operations. The study contributes to the understanding of the integration of EV charging infrastructure with smart city concepts and informs the design and implementation of efficient and sustainable charging solutions in urban environments.

2.2 Off Board DC Charger

The article titled "A new off-board electrical vehicle battery charger: topology, analysis, and design" was published in the journal Designs in 2021. The authors of the article are F. M. Shahir, M. Gheisarnejad, M. S. Sadabadi, and M.-H. Khooban.[**8**]

The study presents a new design of an off-board electrical vehicle (EV) battery charger. The authors introduce a novel topology and provide an in-depth analysis and design considerations for the charger. The article begins by discussing the need for efficient and reliable off-board chargers to support the charging of EV batteries from external power sources. The authors emphasize the importance of high-efficiency chargers that can handle different charging requirements and minimize energy losses.

The study introduces a new charger topology specifically designed for off-board charging applications. The authors provide a detailed analysis of the proposed topology, considering factors such as power conversion efficiency, voltage regulation, and current ripple. They also discuss the advantages of the new design, such as reduced size, improved power quality, and enhanced reliability.

Furthermore, the article discusses the design considerations and methodology for implementing the proposed charger topology. The authors describe the selection and integration of key components, such as transformers, rectifiers, filters, and control circuits. They discuss the challenges associated with high-frequency operation, thermal management, and electromagnetic compatibility.

The study includes simulation results and performance analysis of the proposed charger. The authors evaluate its efficiency, power factor, voltage regulation, and other relevant parameters. They compare the performance of the new charger with existing topologies to demonstrate its advantages and effectiveness.

Overall, the article presents a new off-board electrical vehicle battery charger design. It provides a detailed analysis of the charger topology, design considerations, and performance evaluation. The study contributes to the understanding of charger design for EV applications and offers insights for the development of efficient and reliable charging solutions.

The article titled "An off-board multi-functional electric vehicle charging station for smart homes: Analysis and experimental validation" was published in the journal Energies in 2020. The authors of the article are V. Monteiro, P. Lima, T. J. Sousa, J. S. Martins, and J. L. Afonso.[**13**]

The study presents the analysis and experimental validation of an off-board multi-functional electric vehicle (EV) charging station designed for smart homes. The authors propose a charging station that integrates various functionalities and technologies to enhance the charging process and enable smart grid interactions.

The article begins by discussing the importance of integrating EV charging infrastructure with smart homes to promote energy efficiency and grid integration. The authors highlight the potential benefits of multi-functional charging stations that can provide advanced functionalities beyond conventional charging.

The study presents the design and analysis of the proposed off-board multi-functional charging station. The authors describe the key components and functionalities of the charging station, including bidirectional power flow, energy storage integration, renewable energy utilization, and smart grid interactions. They discuss the advantages of each component and its contribution to the overall performance of the charging station.

Furthermore, the authors provide experimental validation of the charging station through simulations and real-world tests. They evaluate the performance and efficiency of the multi-functional charging station under different scenarios and load conditions. The experimental validation provides insights into the actual performance and feasibility of the proposed design.

The article also discusses the potential benefits and applications of the off-board multi-functional charging station. The authors explore the possibilities of demand response, load management, and energy cost optimization through the integration of EV charging with smart home energy management systems. They highlight the potential of the charging station to support grid stability, renewable energy integration, and user convenience.

Overall, the article presents the analysis and experimental validation of an off-board multi-functional electric vehicle charging station for smart homes. It highlights the integration of advanced functionalities and technologies to enhance the charging process and enable smart grid interactions. The study contributes to the development of efficient and sustainable charging solutions and informs stakeholders about the potential benefits and feasibility of multi-functional charging stations for EVs in smart home environments.

The article titled "State-of-the-art vehicle-to-everything mode of operation of electric vehicles and its future perspectives" was published in the journal Renewable and Sustainable Energy Reviews in 2022. The authors of the article are S. Islam, A. Iqbal, M. Marzband, I. Khan, and A. M. Al-Wahedi.[**12**]

The study provides a comprehensive review of the state-of-the-art vehicle-to-everything (V2X) mode of operation of electric vehicles (EVs) and explores its future perspectives. V2X refers to the capability of EVs to interact and exchange energy with various entities in the surrounding ecosystem, including the grid, buildings, other vehicles, and users.

The article begins by discussing the concept and importance of V2X technology in the context of smart grids and sustainable transportation. The authors highlight the potential benefits of V2X, such as grid support, energy management, demand response, vehicle-to-grid (V2G) integration, and enhanced user experience.

The study provides an overview of the different modes of V2X operation, including vehicle-to-grid (V2G), vehicle-to-home (V2H), vehicle-to-building (V2B), and vehicle-to-vehicle (V2V). The authors analyze the characteristics, functionalities, and applications of each mode, considering factors such as power flow, energy management, load balancing, and grid stability.

Furthermore, the article discusses the state-of-the-art technologies and research developments in V2X operation. The authors explore the communication protocols, control strategies, and hardware requirements for enabling V2X capabilities in EVs. They discuss the challenges associated with V2X implementation, including interoperability, standardization, cybersecurity, and infrastructure readiness.

The study also explores the future perspectives and potential advancements in V2X technology. The authors discuss emerging trends, such as dynamic charging, bidirectional power flow, and advanced control algorithms. They analyze the impact of V2X on the energy system, transportation sector, and urban environments, highlighting its potential to support renewable energy integration, grid stability, and sustainable mobility.

Overall, the article provides a comprehensive review of the state-of-the-art vehicle-to-everything mode of operation of electric vehicles. It discusses the different V2X modes, technologies, challenges, and future perspectives. The study contributes to the understanding of V2X technology and its potential in transforming the energy and transportation sectors towards a more sustainable future.

2.3 Previous Studies on Repurposing EV Components

This section presents an overview of previous studies that have explored repurposing EV components, including batteries and power electronics, for various applications. It highlights the potential benefits of repurposing these components, such as reduced waste, cost savings, and resource conservation.

The article titled "Simulation and hardware development of AC-DC power converter for off-board charger of EV" was published in Materials Today: Proceedings in 2022. The authors of the article are R. Seyezhai, A. B. S. Ammaiyappan, N. Heera, P. Keerthana, and M. Srinivasan. [**3**]

The study focuses on the simulation and hardware development of an AC-DC power converter for an off-board charger used in electric vehicle (EV) applications. The off-board charger is a device that is not integrated into the vehicle but is used to charge the EV's battery from an external power source.

The authors describe the process of simulating and developing the AC-DC power converter to convert alternating current (AC) from the power source to direct current (DC) for charging the EV's battery. They discuss the design considerations, such as the converter topology, control strategy, and selection of components.

The simulation phase involves using computer software to model and analyze the behavior of the AC-DC power converter under different operating conditions. The authors examine factors such as efficiency, power factor, and harmonic distortion to evaluate the converter's performance and ensure it meets the required specifications.

In the hardware development phase, the authors implement and test the designed AC-DC power converter in a physical prototype. They discuss the selection and integration of various components, such as transformers, rectifiers, and filters. The hardware development allows them to validate the simulation results and assess the converter's performance in real-world conditions.

The article presents the simulation and hardware development results, discussing the performance and efficiency of the AC-DC power converter. The authors also highlight the challenges faced during the development process and suggest potential improvements for future iterations of the converter design.

Overall, the article provides insights into the simulation and hardware development of an AC-DC power converter for an off-board charger used in EV applications. It contributes to the understanding of the design and performance optimization of power converters for EV charging systems and informs the development of more efficient and reliable charging solutions for electric vehicles.

2.4 Environmental and Economic Implications

This section explores the environmental and economic implications of second life applications for on-board charging systems. It discusses the potential environmental benefits, such as reducing electronic waste, minimizing the environmental impact of manufacturing new components, and lowering carbon emissions through extended product lifecycles.

The article "Life-cycle analysis of charging infrastructure for electric vehicles" [**1**] focuses on the evaluation of the environmental impacts associated with the charging infrastructure required for electric vehicles (EVs). The authors conduct a life-cycle analysis (LCA) to assess the energy consumption and emissions from the entire life cycle of charging infrastructure, including manufacturing, transportation, operation, and disposal phases.

The study considers different types of charging infrastructure, such as home charging units, public charging stations, and battery swapping stations. It analyzes the energy consumption and greenhouse gas emissions associated with these infrastructure types, taking into account the electricity generation mix in the specific region under study.

The authors present the results of their LCA, comparing the environmental impacts of the different charging infrastructure options. They discuss the energy consumption and emissions associated with the manufacturing and operation of the infrastructure, as well as the potential environmental benefits of using renewable energy sources for electricity generation.

Additionally, the article addresses the potential environmental benefits and challenges of implementing charging infrastructure for EVs, including the need for appropriate policies and regulations to promote sustainable charging infrastructure development.

Overall, the article provides insights into the environmental implications of charging infrastructure for electric vehicles, highlighting the importance of considering the full life cycle of the infrastructure in order to make informed decisions and promote sustainable transportation solutions.

In summary, the literature review chapter provides a comprehensive analysis of the existing research on second life applications for on-board charging electric power systems in EVs. It covers the components and functionalities of on-board charging systems, explores the concept of second life applications, discusses previous studies on repurposing EV components, and examines the environmental and economic implications of repurposing. The review identifies gaps in the current knowledge and sets the stage for the research objectives outlined in the subsequent chapters.

The article titled "Optimal allocation of electric vehicles charging infrastructure, policies and future trends" was published in the Journal of Energy Storage in 2021. The authors of the article are R. S. Gupta, A. Tyagi, and S. Anand.[**4**]

The study focuses on the optimal allocation of charging infrastructure for electric vehicles (EVs) and explores the associated policies and future trends. The authors address the challenges and considerations involved in designing an efficient and effective charging infrastructure network to support the growing adoption of EVs.

The article discusses the importance of optimal charging infrastructure allocation in terms of location, capacity, and type of charging stations. The authors analyze various factors such as travel patterns, charging demands, and electricity grid constraints to identify the most suitable locations for charging stations. They also consider factors like charging technologies, charging speeds, and the compatibility of charging infrastructure with different types of EVs.

The study emphasizes the role of policies in promoting the development and deployment of charging infrastructure. The authors discuss different policy mechanisms, such as financial incentives, regulations, and standards, which can incentivize investment in charging infrastructure and support its efficient utilization. They also explore the impact of policy frameworks on market growth, user behavior, and overall EV adoption.

Furthermore, the article highlights future trends and emerging technologies in EV charging infrastructure. The authors discuss advancements in fast-charging technologies, wireless charging, vehicle-to-grid integration, and smart charging systems. They explore how these trends can enhance the efficiency, convenience, and sustainability of charging infrastructure.

Overall, the article provides insights into the optimal allocation of EV charging infrastructure, the significance of policies in supporting its development, and the future trends shaping the field. It contributes to the understanding of the planning and design of charging infrastructure networks and informs the formulation of effective policies to foster the growth of sustainable transportation through EV adoption.

The article titled "Analysis on business development and pricing for electric vehicle charging in Indonesia" was presented at the 2021 3rd International Conference on E-Business and E-commerce Engineering. The authors of the article are B. Santoso and W. Wahyu Purwanto.[**5**]

The study focuses on analyzing the business development and pricing aspects of electric vehicle (EV) charging in Indonesia. The authors examine the current state of EV charging infrastructure in Indonesia and explore the challenges and opportunities for business development in this sector.

The article discusses the importance of developing a robust and sustainable business model for EV charging services. The authors analyze the various stakeholders involved in the charging ecosystem, such as EV owners, charging station operators, utilities, and government entities. They highlight the need for collaboration and coordination among these stakeholders to ensure the effective deployment and operation of charging infrastructure.

Furthermore, the study addresses the pricing strategies for EV charging in Indonesia. The authors consider factors such as electricity tariffs, infrastructure costs, and consumer demand patterns to assess the appropriate pricing models. They discuss different pricing mechanisms, including flat rates, time-based rates, and dynamic pricing, and analyze their implications for the viability of charging station businesses and the affordability for EV owners.

The article presents the analysis of business development opportunities and pricing strategies in the context of Indonesia's EV charging market. It provides insights into the challenges and considerations involved in establishing a sustainable charging infrastructure network and offers recommendations for policy frameworks and business models that can support the growth of the EV charging sector.

Overall, the article contributes to the understanding of the business aspects and pricing dynamics of EV charging in Indonesia. It informs stakeholders about the opportunities and challenges associated with developing and operating charging infrastructure in the country and suggests strategies for fostering the adoption of electric vehicles through a well-designed charging ecosystem.

The article titled "Design and prospective assessment of a hybrid energy-based electric vehicle charging station" was published in the journal Sustainable Energy Technologies and Assessments in 2022. The authors of the article are V. Boddapati, A. R. Kumar, S. A. Daniel, and S. Padmanaban.[**11**]

The study presents the design and prospective assessment of a hybrid energy-based electric vehicle (EV) charging station. The authors propose a charging station that integrates multiple energy sources to provide reliable and sustainable charging for EVs.

The article begins by discussing the importance of developing charging stations that utilize renewable energy sources to reduce environmental impact and promote sustainable transportation. The authors emphasize the need for reliable charging infrastructure that can accommodate the increasing number of EVs on the road.

The study presents the design of the hybrid energy-based charging station. The authors discuss the integration of different energy sources, such as solar power, wind power, and energy storage systems. They describe the components and functionalities of the charging station, including renewable energy generators, power conversion systems, energy management systems, and charging infrastructure.

Furthermore, the authors conduct a prospective assessment of the proposed charging station. They analyze the performance and feasibility of the hybrid energy system, considering factors such as energy production, reliability, cost-effectiveness, and environmental impact. The assessment includes simulations, modeling, and analysis to evaluate the potential benefits and challenges of the charging station design.

The article also discusses the implications and future prospects of the hybrid energy-based charging station. The authors address issues related to scalability, grid integration, policy support, and user acceptance. They highlight the potential of the proposed charging station in reducing greenhouse gas emissions, promoting renewable energy utilization, and supporting sustainable transportation in the long run.

Overall, the article presents the design and prospective assessment of a hybrid energy-based electric vehicle charging station. It emphasizes the importance of integrating renewable energy sources into charging infrastructure and provides insights into the performance and feasibility of such a system. The study contributes to the development of sustainable charging solutions and informs stakeholders about the benefits and challenges associated with hybrid energy-based charging stations for EVs.

3
Theory

This chapter introduces fundamental theoretical foundations related to diverse technologies, methodologies, and executions for adapting the current OBCs for new purposes. The OBC supplied by VOLVO GTT is also showcased, complete with functional and design specifications. These explanations will assist in identifying the most suitable approach for creating a functional repurposed, compact off-board charger for electric vehicles.

3.1 On Board Charger

The on-board charger (OBC) plays a crucial role in electric vehicles (EVs), enabling them to directly charge from the AC grid. This technology is widely embraced in the automotive sector due to its convenience, especially when contrasted with the high-cost and space-intensive off-board charging alternatives [**17**] – [**20**]. Among OBCs, unidirectional versions stand out due to their uncomplicated hardware prerequisites and minimal battery deterioration [**21**]. However, the evolution of EVs has brought to light their potential as mobile energy reservoirs. Indeed, bidirectional OBCs have emerged with the capability to support vehicle-to-grid (V2G) functionality by feeding surplus electrical energy back to the grid, which proves invaluable during peak power demands [**22**], [**23**]. Beyond this, bidirectional OBCs extend the possibilities for EV owners, allowing them to utilize their vehicles for other applications such as furnishing vehicle-to-home (V2H) or vehicle-to-load (V2L) power during grid outages, and even enabling vehicle-to-vehicle (V2V) interactions during emergencies [**24**]–[**26**]. There are two main known architectures known as Two Stage and Single stage respectively, where we have separate AC/DC and DC/DC converters with a DC link between both whereas single stage has only an AC/DC module and the DC link is not used as depicted in Figure 3.1.

3.1.1 AC/DC Converter

The AC/DC converter is composed of a Full-bridge rectifier and a Boost PFC converter. This particular converter configuration offers several advantages, including the ability to maintain a low Total Harmonic Distortion (THD) in the input current, encompassing harmonics. Moreover, it boasts a straightforward converter design and the capability to maintain a moderate power factor. However, there is a notable correlation between the size of the Boost PFC converter and the power it

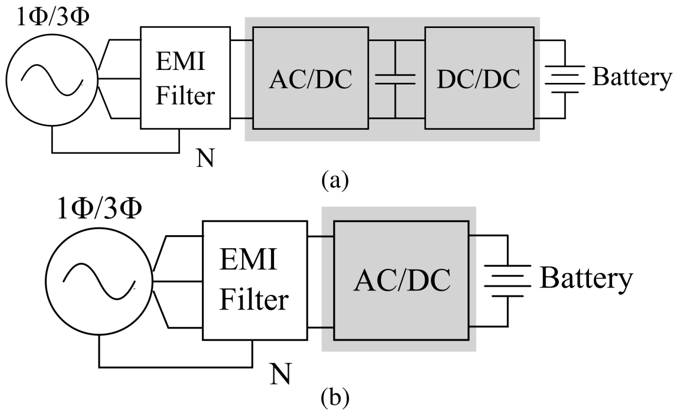


Figure 3.1: (a) Two Stage Architecture (b) Single Stage Architecture [**27**]

delivers. Consequently, as the required high-power output increases, the converter itself expands in size [**28**].

3.1.2 PFC Controller

To achieve a sinusoidal AC output current with minimal phase shift between the current and voltage, the presence of an operational control system within the circuit is of utmost importance. Typically, this control system takes the form of a closed-loop control mechanism, often designed as a PI- or PID controller, which regulates the switching of the gate using PWM signals [**29**]. The gate's operation alternates between on and off modes to ensure that the inductor current aligns with the predetermined reference values. In essence, the Power Factor Correction (PFC) controller enforces a synchronization of current draw in accordance with the input voltage [**30**]. However, given that the error amplifier within the controller operates at a relatively slow pace, it might necessitate several power line cycles before the resulting output stabilizes [**31**].

The controller takes inputs in the form of output voltage measurements, reference voltage, AC input voltage, and the averaged chopped inductor current. These inputs are then compared with their corresponding reference values by the controller, which subsequently determines the amplitude and duty cycle of the PWM signal. In cases where disparities arise between the measured values and their reference counterparts, adjustments are made to the PWM signal. These adjustments involve modifying the duty cycle, contingent upon the necessary level of Boost.

3.1.3 DC Link

A DC link, alternatively referred to as a capacitor bank, serves as an intermediary stage positioned between an input stage and an output stage. This DC link is typically comprised of a capacitor, bridging between two other capacitors with distinct positive and negative terminals. These stages are interconnected via the DC link, as depicted in Figure 3.1. In scenarios involving a common input stage such as an

AC/DC converter (rectifier) with a Power Factor Correction (PFC) circuit, the DC link operates as an output filter, mitigating voltage ripple. To attenuate voltage ripple and enhance power factor by reducing reactive power, it proves advantageous to parallel-connect multiple capacitors with appropriately calculated dimensions [**32**]. As for the output stage, it usually integrates a converter with switching capabilities or an inverter. In cases where the AC/DC converter is engaged in high-power mode, the capacitance value is minimized to maximize energy storage capacity. Conversely, converters in low-power mode require reduced capacitance to ensure that voltage ripple does not interfere [**33**].

3.1.4 DC/DC Converter

A DC/DC converter refers to an electrical circuit designed to transition from one DC value to another. In detail, the initial step involves rectifying the incoming voltage to achieve a DC state. This is succeeded by employing switching components to transform the voltage into high-frequency AC voltage. Subsequently, this AC voltage is reconverted to the desired DC output voltage [**33**].

Within the context of an On-Board Charger (OBC), an isolated Full-bridge DC/DC converter is employed. This converter features a transformer that provides isolation in applications requiring high power. This isolation is especially crucial during battery charging. On the primary side of the transformer, four switches are present. In this particular instance, metal-oxide-semiconductor field-effect transistors (MOSFETs) are utilized to establish a Full-bridge configuration. The battery side can be constructed with ZVS diodes as a rectifier configuration to reduce losses for unidirectional power supply, else MOSFET-based Full bridge configuration is implemented to enable bidirectional flow of power when required to work under the mode of V2X.

3.1.5 Filter

Filters are passive components that play a vital role in the reduction of THD or disturbances that are found in the current and voltage of power supplied to the power electronic components. The Filter has to be designed appropriately such that the THD component remains well under 8% according to EN 50160 [**34**]. In real life, filters can be built using a combination of passive components such as inductors and capacitors. The filters can be built in various configurations such a π filter, L-filter or T-filter [**35**].

3.2 Power Factor Correction

To achieve optimal power quality during the design of AC/DC converters, it is essential to adhere to international standards by establishing a reasonable Power Factor (PF) and Total Harmonic Distortion (THD). The Power Factor, denoted as the ratio of real power (P) to apparent power (S), assumes significance. In cases where a phase-shift exists between sinusoidal current and voltage waveforms, the equation can be represented as [36].

$$PF = \frac{P}{S}$$

Given that real power represents the transferred element, it becomes crucial to minimize reactive power (Q). This approach contributes to achieving a Power Factor (PF) nearer to 1.0, often referred to as unity, where active power aligns with apparent power. When sinusoidal current and voltage waveforms are in sync, it indicates a PF approaching 1.0, which is termed as a linear load [29]. Conversely, if the waveforms are sinusoidal but not synchronized, the PF deviates from 1.0, characterizing a non-linear load [36][37].

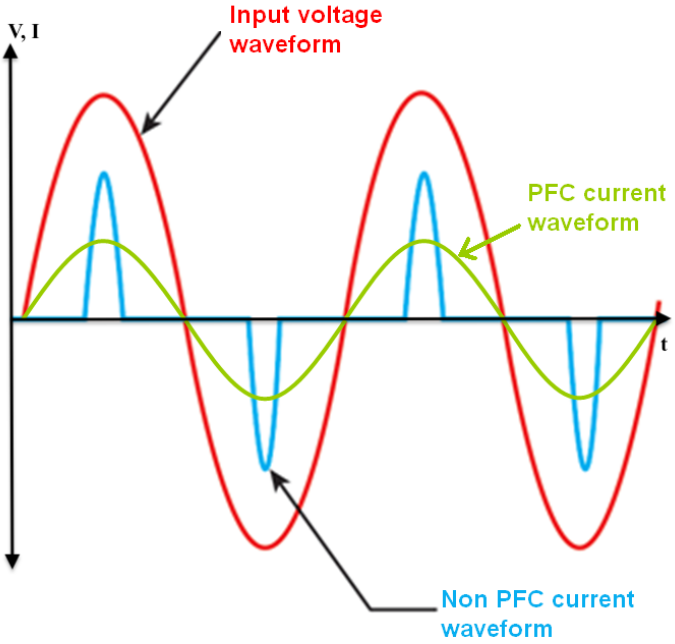


Figure 3.2: Graph depicted the flow of current and voltage in presence and absence of PFC [38]

To mitigate distortion and ensure synchronization of input current with input voltage – a condition known as a resistive load – the implementation of power factor correction (PFC) becomes essential. This correction enhances overall power quality, resulting in reduced current harmonics, minimized output voltage ripple, heightened efficiency, provision for multiple output voltage levels, rapid output dynamics, and effective load regulation. Notably, adhering to international standards such as IEC 61000-3-2 and IEEE-519 mandates the inclusion of PFC in AC/DC converters [36].

A power supply equipped with PFC is anticipated to maintain a power factor within the range of 0.95-0.99, while a power supply lacking PFC typically exhibits a power factor ranging from 0.70-0.75 [39].

3.3 AC/DC Converter Topologies

The AC/DC converter can be modelled in various topologies and semiconductor devices such as diode's, MOSFET's and IGBT's. The diodes being a passive does not provide any control to the user, on the other hand MOSFET's and IGBT's provide a fully controlled environment making it robust and resilient to be used in modern day equipment's.

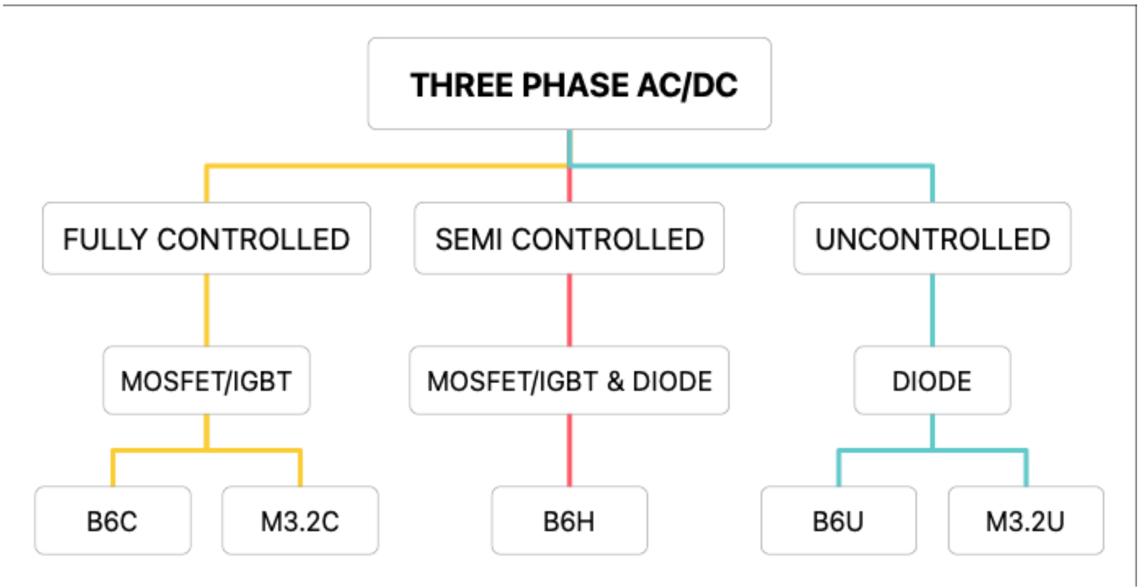


Figure 3.3: Categorization of AC/DC converter

3.3.1 B6C

The B6C topology is widely used in the modern equipment's which require complex control systems in form of high resiliency and fidelity to ensure that the system is dynamic in nature. It is a fully controlled three-phase rectifier housing 6 controllable semiconductor switches IGBT's or MOSFET's. The Figure 3.4 depicts a barebone structure of a B6C circuit.

3.3.2 B6U

The B6U topology is widely used in the modern equipment's which does not require complex control systems if the system is fixed in nature. It is an controlled three-phase rectifier housing 6 diodes which works on the principle of passive switching techniques. The Figure 3.5 depicts a barebone structure of a B6C circuit.

3.3.3 B6H

The B6H topology is considered a semi controlled approach which houses 3 MOSFET's/IGBT's and 3 diodes for conversion of three phase AC to a DC supply. The Figure 3.6 depicts a barebone structure of a B6C circuit.

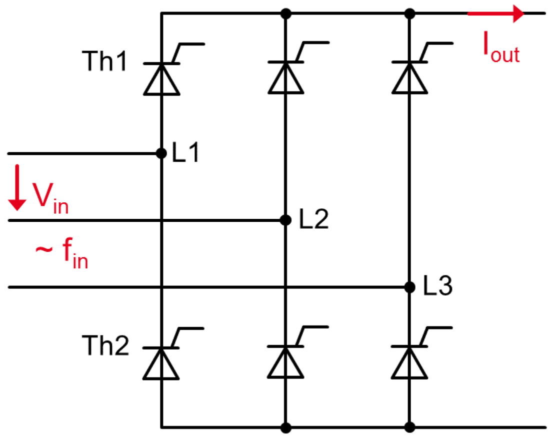


Figure 3.4: Fully controlled three-phase rectifier with 6 thyristors/MOSFETS

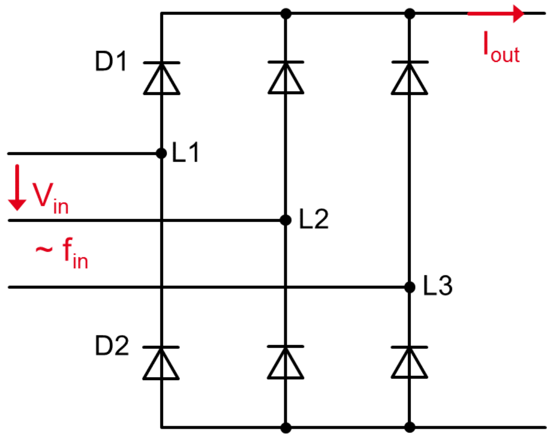


Figure 3.5: Uncontrolled three-phase rectifier with 6 diodes

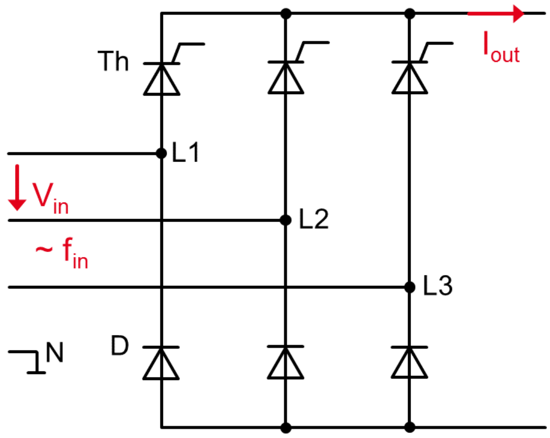


Figure 3.6: Half-controlled three-phase rectifier with 3 thyristors/MOSFETS and 3 diodes

3.3.4 M3-2C

The M3.2C topology is widely used in the modern equipment's which require complex control systems in form of high resiliency and fidelity to ensure that the system is dynamic in nature. It is a fully controlled three-phase rectifier housing 6 controllable semiconductor switches IGBT's or MOSFET's in the configuration of star connection. The Figure 3.7 depicts a barebone structure of a M3.2C circuit.

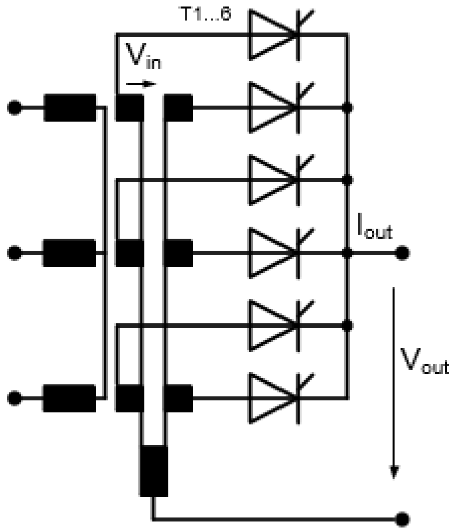


Figure 3.7: Double Three-Pulse Star Fully Controlled with 6 MOSFETS

3.3.5 M3-2U

The M3.2U topology is widely used in the modern equipment's which does not require complex control systems if the system is fixed in nature. It is an controlled three-phase rectifier housing 6 diodes in a star connection, which works on the principle of passive switching techniques. The Figure 3.8 depicts a barebone structure of a M3.2U circuit.

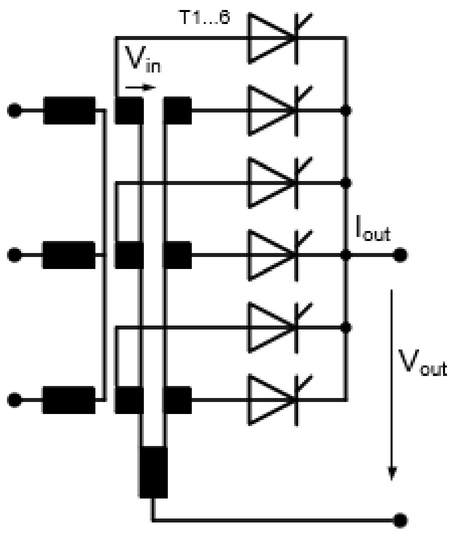


Figure 3.8: Double Three-Pulse Star Uncontrolled with 6 diodes

The cost with respect to ability to control was tabulated as shown in Table **??**.

Topology	No. of MOSFET	No. of Diode	Cost	Controllability
B6U	0	6	Low	Uncontrolled
B6H	3	3	Medium	Semi Controlled
B6C	6	0	High	Fully Controlled
M3.2C	6	0	High	Fully Controlled
M3.2U	0	6	Low	Uncontrolled

Table 3.1: Summary of findings for various topology

3.4 Introduction to OCEPS

The Onboard Charging Electric Power Supply (OCEPS), is a power module widely used in trucks with the capability of operating in bidirectional mode supporting Grid to Vehicle (G2V), Vehicle to Load (V2L) and serve as a power module for normal operation of electric propulsion system.

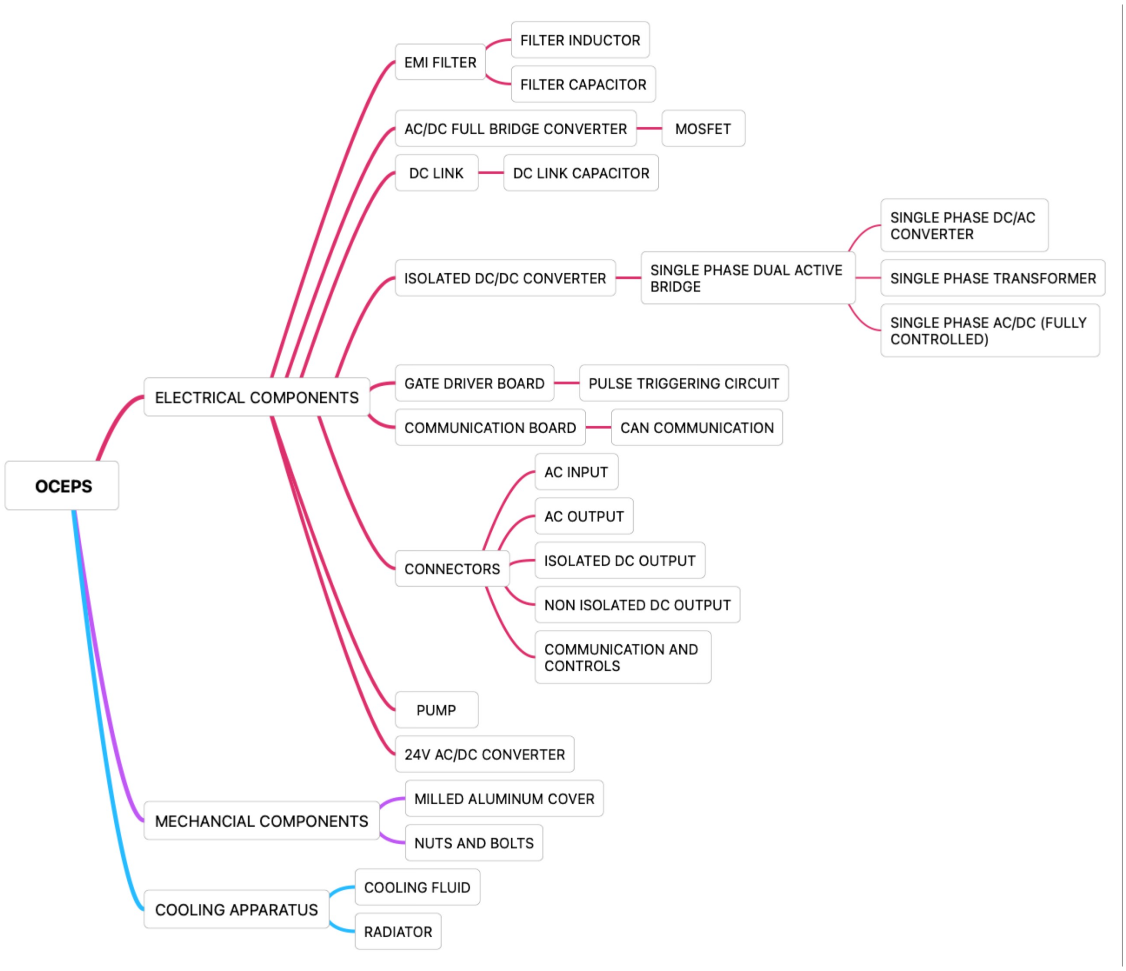


Figure 3.9: Components Classification in an OCEPS

The OCEPS power module consists of a combination of Front End Converter (FEC) with Power Factor Correcting Circuit (PFC) and isolated DC-DC converter to en-

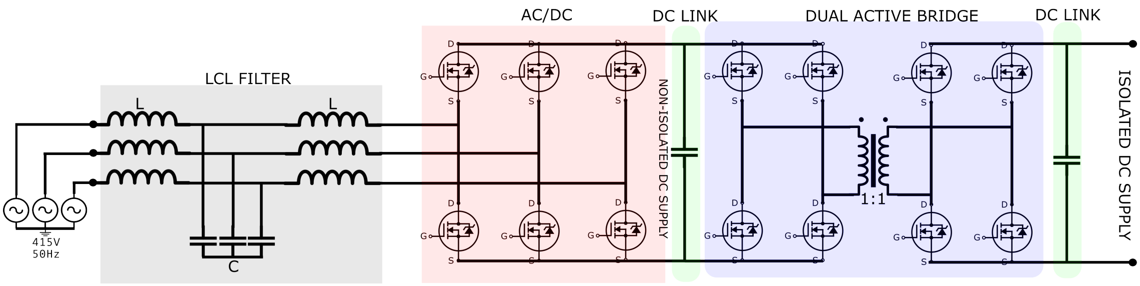


Figure 3.10: Overall Electrical Diagram of an OCEPS

hance the aspect of safety and abide by the regulations set up to meet the industry standards as depicted in Figure 3.10

3.5 Metal Oxide Semiconductor Field Effect Transistor - MOSFET

MOSFET is a semiconductor device used widely in power electronic circuits which can be used to design several converters like step up, step down, rectifiers, inverters etc. It is also known for its non linear nature and possibility to be fully controlled based on triggering pulses based on the requirements.

3.5.1 Various operating modes of MOSFET [16]

Since MOSFET being a semiconductor it has a non linear curve of operation as shown in Figure 3.12. The MOSFET operates in three various conditions such as Turn on, Conduction and Turn off modes where the internal capacitance and the rise time differs with respect to the operation.

3.5.1.1 Turn On Condition

A MOSFET turn on is classified into three different parts where the internal parameters changes as mentioned.

$$\begin{cases} V_{gs} \text{ rises to } V_{gs,th} \text{ from Zero} \\ V_{gs} \text{ rises to } V_{gs,i0} \text{ from } V_{gs,th} \\ I_d = I_0 \end{cases}$$

Initially when the gate driver is turned on, the gate voltage V_{gs} rises from 0 to $V_{gs,th}$. The equivalent circuit while this operation is depicted in Figure 3.11

The equation governing this situation is calculated to be

$$i_G = \frac{C_{eq} dv_{gs}}{dt} = \frac{V_{GG} - v_{gs}}{R_G}$$

Solving this first oder equation we get

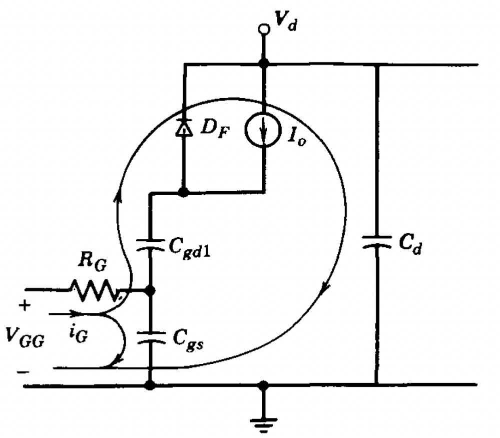


Figure 3.11: MOSFET turn on case 1

$$v_{gs}(t) = V_{GG}(1 - e^{(\frac{-t}{\tau})})$$

$$\tau = (C_{gd} + C_{gs})R_G$$

The turn on delay time until the V_{gs} rises from 0 to $V_{gs,th}$

$$t_{d,on} = -\tau \ln[\frac{V_{GG} - V_{gs,th}}{V_{GG}}]$$

Once the voltage reaches $V_{gs,th}$, i_d takes a time of t_{ri}.

$$t_{v_{gs,I0}} = -\tau \ln[\frac{V_{GG} - V_{gs,I0}}{V_{GG}}]$$

$$t_{ri} = t_{v_{gs,I0}} - t_{d,on}$$

After the turn on, the C_{gs} cannot participate in the mode of conduction, hence the equation slightly modifies to

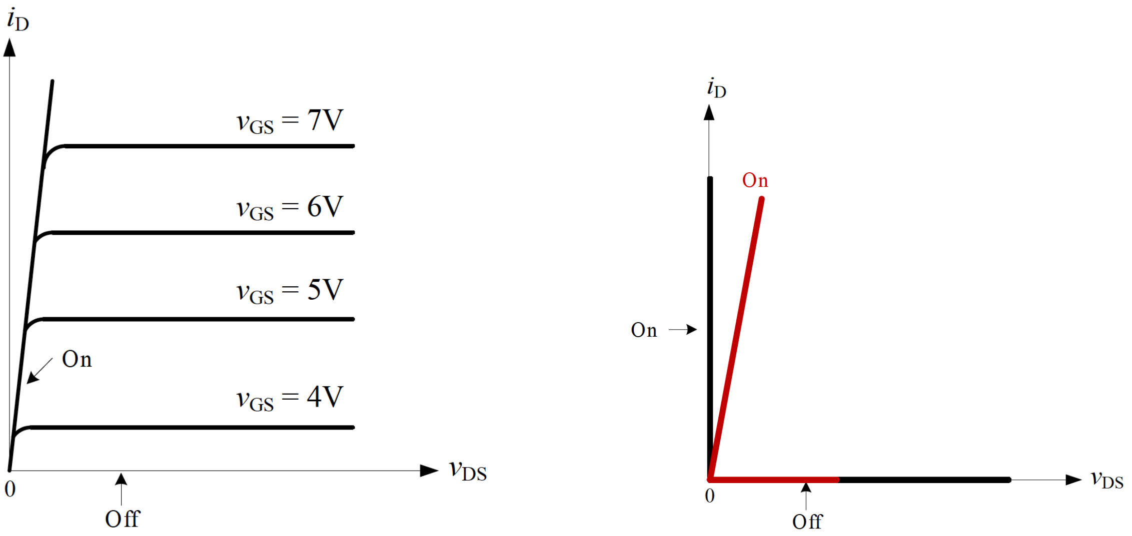
$$i_g = \frac{V_{GG} - V_{gs,I0}}{R_G} = C_{gd}\frac{dv_{gd}}{dt}$$

Since, $V_{ds} = V_{dg} + V_{gs}$ and $v_{gs}(t) = v_{gs,I0}$

$$\frac{dv_{ds}}{dt} = \frac{dv_{dg}}{dt} = -\frac{dv_{gd}}{dt} = -\frac{V_{GG} - V_{gs,I0}}{C_{gd}R_G}$$

Substituting $V_{ds}(0) = V_d$

$$v_{ds}(t) = V_d - \frac{V_{GG} - V_{gs,I0}}{C_{gd}R_G}t$$



(a) i-v characteristic

(b) idealized characteristic

Figure 3.12: MOSFET Characteristics

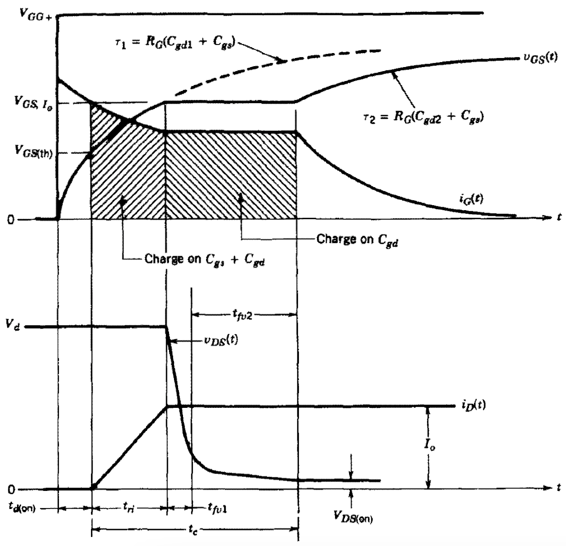


Figure 3.13: Turn on Characteristics

3.6 Loss and Thermal Calculation in MOSFET

MOSFET being a semiconductor device, it is subjected to continuous turn and turn off at very high frequency. The MOSFET is susceptible to two major losses such as conduction loss and switching loss.

Switching Loss is the loss incurred due to multiple turn on and off of the MOSFET. It is directly proportional to the switching frequency.

$$P_{switching} = (E_{sw,on} + E_{sw,off})f_{sw}$$

Conduction Loss is loss incurred due to the state of conduction. It is dependant upon the value of r_{ds}.

$$P_{conduction} = I^2 R_{ds}$$

The total power loss can be equated as

$$P_{total} = P_{switching} + P_{conduction}$$

The combined power loss causes increases in the temperature as it dissipates as heat. The junction temperature of the MOSFET in such condition can be formulated as

$$T_j = P_{total}(R_{\theta,jc} + R_{\theta,cs} + R_{\theta,sa}) + T_a$$

3.7 Dual Active Bridge Converter (DAB)

The Dual Active Bridge (DAB) is a very prominent DC-DC converter which provides circuit isolation and capable of providing bidirectional transfer of power. It is also known for its nature of high power density and easy implementation of Zero voltage switching (ZVS) and easily scalable by cascading. [**15**]

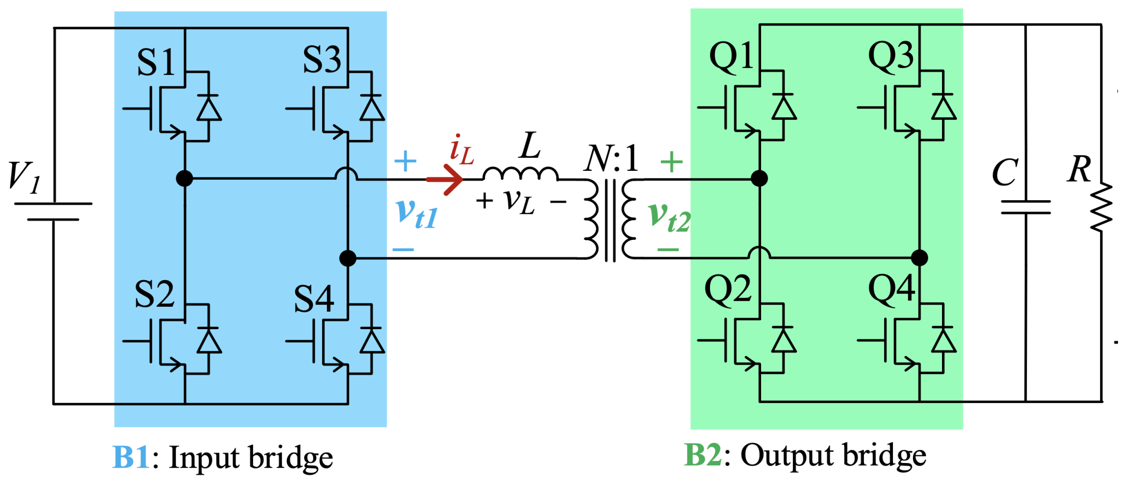


Figure 3.14: Dual Active Bridge (DAB) Circuit

The power transmitted in a DAB converter can be simplified into an equation described below:

$$P = \frac{V_{rms1} V_{rms2}}{2\pi f L} sin\Phi$$

Where, V_{rms1} and V_{rms2} are the RMS values of voltages with source frequency f and phase shift Φ between source and load. Assuming a Bipolar pulsating voltage having 50% duty cycle we can observe the characteristic waveform as depicted in Figure 3.15.

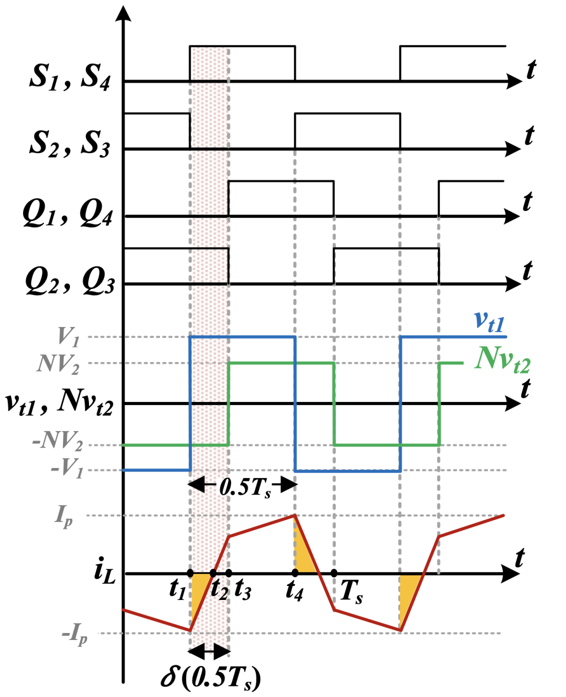


Figure 3.15: DAB waveform of gate signal, voltages and inductor current in SPS

When the DAB is controlled using an SPS the power transferred equation can be rewritten as

$$P = \frac{NV_2V_1}{2\pi^2 L f_s}\Phi(\pi - |\Phi|)$$

The Power transmitted in the positive direction can be formulated as

$$P = \frac{1}{T_s}\int_0^{T_s} V_{t1} i_L dt = \frac{2}{T_s}V_1\int_0^{0.5T_s} i_L dt$$

Considering all four time intervals in one complete cycle, the value of inductor current depicted in Figure 3.15 can be written as:

$$\begin{cases} i_L(t_1) = -I_p \\ i_L(t_2) = 0 \\ i_L(t_3) = i_L(t_1) + \frac{V_1+NV_2}{L}(\frac{\delta T_s}{2}) \\ i_L(t_4) = i_L(t_3) + \frac{V_1-NV_2}{L}(\frac{(1-\delta)T_s}{2}) = I_p \end{cases}$$

By Using the above cases we can find the maximum transmitted power and peak current values as :

$$I_{P,SPS} = \frac{V_1 - NV_2(1-2\delta)}{4Lf_s}$$

$$P_{SPS} = \frac{NV_2V_1}{2Lf_s}\delta(1-\delta)$$

Hence Maximum Power transferred at $\delta = 0.5$

$$P_{SPS} = \frac{NV_2V_1}{8Lf_s}$$

3.8 Control of OCEPS

Every Power electronic circuit requires a logical circuit which helps in proper control of the module. Any carefully designed circuit requires an optimum working control logic to work as expected and debug itself when under any deviations.

This OCEPS model showcases a combination of Current control, Phase Locked Loop (PLL), voltage control and a gate driver logic to generate required Pulse Width Modulation Signals (PWMs) for the MOSFET's while converting AC-DC and DC-AC.

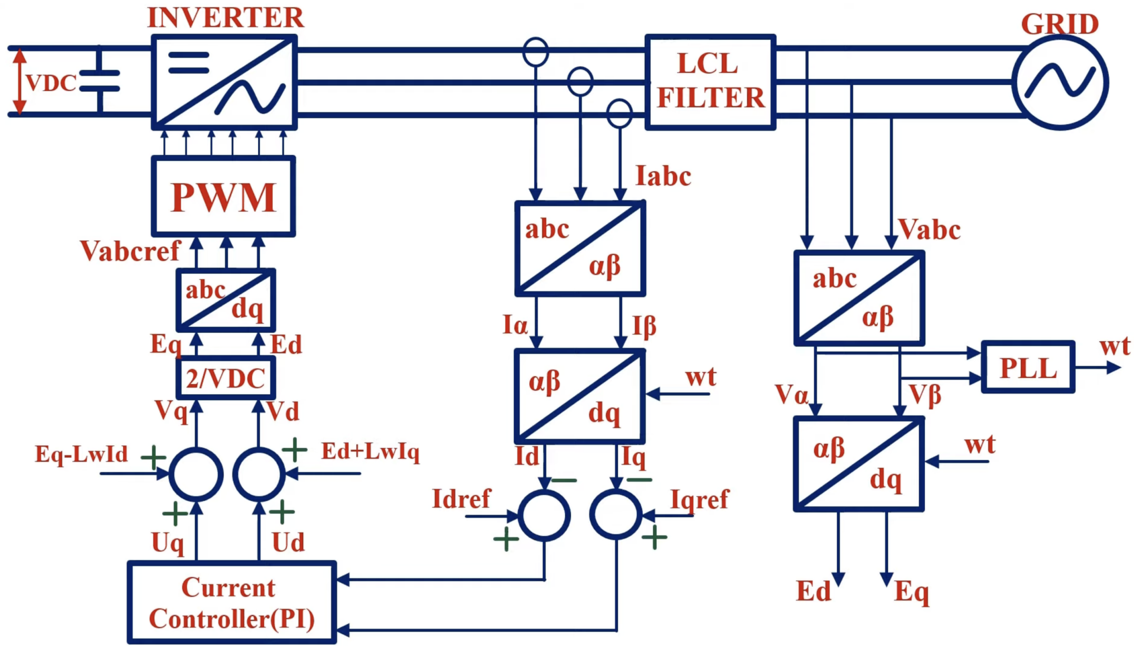


Figure 3.16: OCEPS Control Block Diagram

Initially the 3ϕ Voltage is converted to Stationary framework by applying Park's transformation

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -0.5 & \frac{\sqrt{3}}{2} & 1 \\ -0.5 & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix}$$

The V_α and V_β is used to calculate ωt through Phase Locked Loop by assuming V_d is completely aligned with the voltage and V_q is assumed to be zero.

The V_α and V_β is converted to V_d and V_q by using Clark's transformation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \begin{bmatrix} cos(\omega t) & sin(\omega t) & 0 \\ -sin(\omega t) & cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E_d \\ E_q \\ E_0 \end{bmatrix}$$

Similarly the 3ϕ current is converted to Stationary framework by applying Park's transformation

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -0.5 & \frac{\sqrt{3}}{2} & 1 \\ -0.5 & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix}$$

The I_α and I_β is converted to I_d and I_q by using Clark's transformation.

$$\begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} = \begin{bmatrix} cos(\omega t) & sin(\omega t) & 0 \\ -sin(\omega t) & cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix}$$

In the above equation I_d and I_q corresponds to active and reactive currents. The error is fed into the Current controller after subtracting the reference currents I_{dref} and I_{qref}. The output of current controller provides the value of U_d and U_q.

Similarly we calculate the reference voltages V_d and V_q for the PWM generation

$$V_d = U_d + E_d + L\omega I_q$$

$$V_q = U_q + E_q - L\omega I_d$$

Where L is the inductance of the filter and ω is the grid frequency.

Considering a Sine PWM modulation for this inverter, the relation between modulation index and inverter voltage is defined as

$$V_d = m_d \frac{V_{dc}}{2}$$

$$V_q = m_q \frac{V_{dc}}{2}$$

To eliminate the chance and issues regarding over modulation we multiply the V_d and V_q with $\frac{2}{V_{dc}}$ to obtain the E_{dref} and E_{qref}.

The E_{dref} and E_{qref} is transformed into 3 phase Voltage and fed into PWM generation block considering a Sine PWM modulation with unipolar switching.

4

Results

4.1 Design of LCL Filter

Considering the Per-phase equivalent circuit of a three phase LCL filter can be depicted as in Figure 4.1.

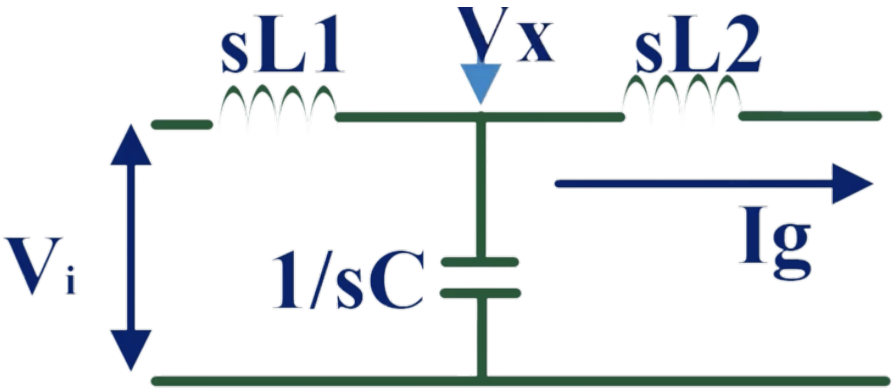


Figure 4.1: Per phase equivalent of LCL filter

By Applying Kirchoffs Current at point "x" and converting them into laplace domain we get:

$$\frac{V_i - V_x}{sL_1} = I_g + \frac{V_x}{\frac{1}{sC}} \tag{4.1}$$

$$V_x = I_g \cdot sL_2 \tag{4.2}$$

By Solving Equation 4.1 and 4.2, we get

$$\frac{I_g}{V_i} = \frac{1}{s^3 L_1 L_2 C + s(L_1 + L_2)} \tag{4.3}$$

Let,

$$L_1 + L_2 = L$$

$$L_p = \frac{L_1 L_2}{L_1 + L_2}$$

Then Equation 4.3 can be written as

$$\frac{I_g}{V_i} = \frac{1}{s^3L(1 + sCL_p)} \tag{4.4}$$

Where ,

$$\omega_{res} = \frac{1}{\sqrt{CL_p}}$$

The Steps involved in a design of filter are:

1. **Select a suitable switching frequency**
   $(f_{sw} = 30kHz)$

2. **Select a suitable resonant frequency** f_{res}
   (Rule: $f_{res} = 0.1 \cdot f_{sw} = 3000Hz$)

3. **Find the Value of capacitance (C)**

   The value of capacitance can be calculated based on the reactive power requirement of the system. Considering a reactive power (Q) requirement which is 5% of rated Power (S).

   $$Q = \frac{V^2}{\frac{1}{2 \cdot \pi \cdot f_{nom} \cdot C}} = 0.05 \cdot S \tag{4.5}$$

   The Equation 4.5 can be written in terms of C,

   $$C = \frac{0.05 \cdot S}{V^2 \cdot 2 \cdot \pi \cdot f_{nom}} \tag{4.6}$$

   For a 44KVA, 230V p-p @ 50 Hz specification, the capacitance can be calculated as below

   $$C = \frac{0.05 \cdot (\frac{44 \cdot 10^3}{3})}{230^2 \cdot 2 \cdot \pi \cdot 50} = 44.12\mu F \tag{4.7}$$

4. **Finding the value of Inductance**

   By continuing from the Equation 4.4, we know that

   $$\frac{I_g}{V_i} = \frac{1}{s^3L(1 + s^2CL_p)}$$

   Where ,

   $$\omega_{res} = \frac{1}{\sqrt{CL_p}}$$

Hence,

$$\frac{I_g}{V_i} = \frac{1}{sL(1 + \frac{s^2}{\omega_{res}^2})} \tag{4.8}$$

At s →jω_{sw}

$$\frac{I_g(sw)}{V_i(sw)} = \frac{1}{j\omega_{sw}L(1 + \frac{(j\omega_{sw})^2}{\omega_{res}^2})} \tag{4.9}$$

Considering the Magnitude part gives us

$$|\frac{I_g(sw)}{V_i(sw)}| = |\frac{1}{\omega_{sw}L(1 - \frac{\omega_{sw}^2}{\omega_{res}^2})}| \tag{4.10}$$

Re-arranging Equation 4.10 to find L

$$L = |\frac{1}{\omega_{sw} \cdot \frac{I_g(sw)}{V_i(sw)}(1 - \frac{\omega_{sw}^2}{\omega_{res}^2})}| \tag{4.11}$$

$$I_g = \frac{\frac{44.10^3}{3}}{230} = 62.31 \ Amps$$

Considering $I_g(sw)$ to be 0.3% of $I_g = 0.1869$ and $V_i(sw)$ to be 0.9 times $V_g = 207V$

$$L = \frac{1}{(2 * \pi * 30000)(\frac{0.1869}{207})(1 - \frac{(2*\pi*30000)^2}{(2*\pi*3000)^2})} = 59.35\mu H$$

4.2 Design of DC link capacitor

A DC Link capacitor plays an important role in every power electronic component by providing the underlying features:

- It Suppresses the ripple in DC link voltage
- It supplies the load when source is reduced
- It stores surplus power
- It serves as a regulator and stabilizer between the source and load
- The stored energy can fix voltage drop for a limited time known as hold up time.

The DC link capacitor can be calculated based on the underlying formulae:

$$C_{dc} = \frac{P_{rated}}{4 * F_{grid} * (V_{dc}^2 - (V_{dc} - V_{ripple})^2)} \tag{4.12}$$

For a converter with specification of 43KW, 50Hz , 800V DC @ 5% ripple.

$$C_{dc} = \frac{\frac{43}{3}}{4 * 50 * (800^2 - (800 - 40)^2)}$$

$$C_{dc} = 1150\mu F$$

Parameter	Value	Unit
Switching Frequency	30	Khz
Resonant Frequency	3	Khz
Filter Inductor	59.35	μH
Filter Capacitor	44.12	μF
DC Link Capacitance	1150	μF

Table 4.1: Calculated Parametric Value for OCEPS

4.3 Calculation of Total Harmonic Distortion (THD)

While an appropriate filter is designed as per the above calculations, the THD is defined as the measurement of all harmonic disturbances present to the ratio of all harmonic component to the primary fundamental component.

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty}(I_h^2)}}{I_1}$$

4.4 Working of OCEPS

The OCEPS has a versatile operation in terms of use cases such as G2V, V2L, V2H etc. Therefore the OCEPS was simulated in MATLAB SIMULINK based on the calculations of LCL filter and DC link as explained in previous sections and the simulink model is depicted in Figure 4.2.

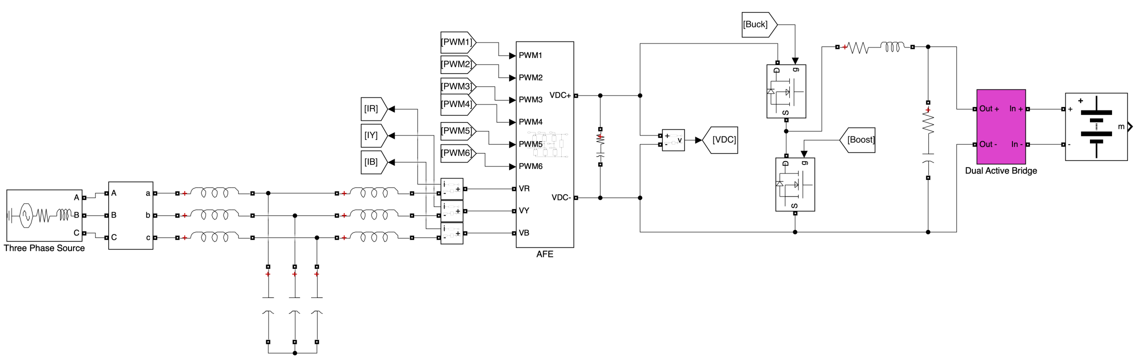


Figure 4.2: OCEPS Model

Based on explanations of controls in previous sections, The necessary conversions and control were implemented to ensure appropriate working of the simulation as depicted in Figure 4.3.

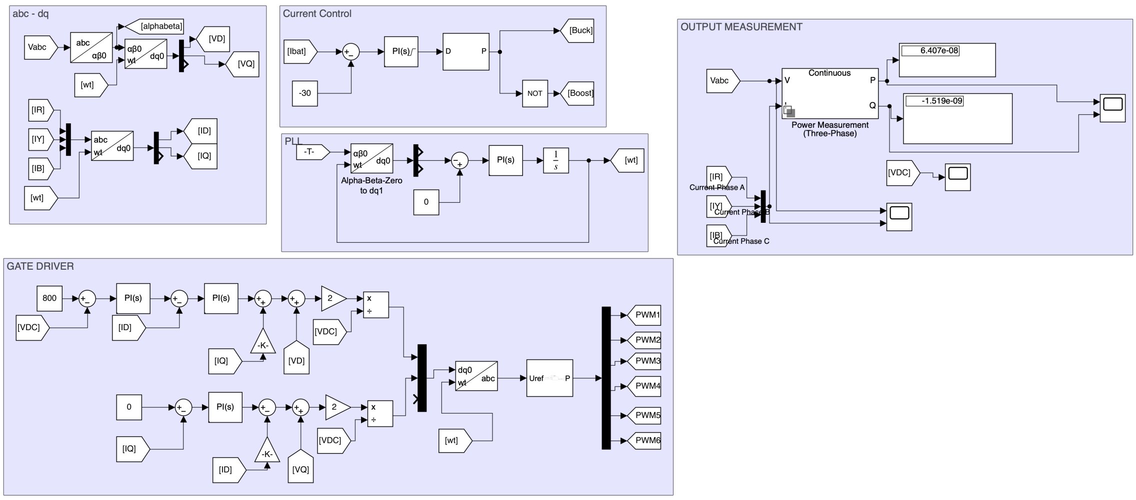


Figure 4.3: OCEPS Control

The Figure 4.4 represents the appropriate transformations between 3ϕ, Stationary and rotating frameworks when the OCEPS is operating under the mode of G2V.

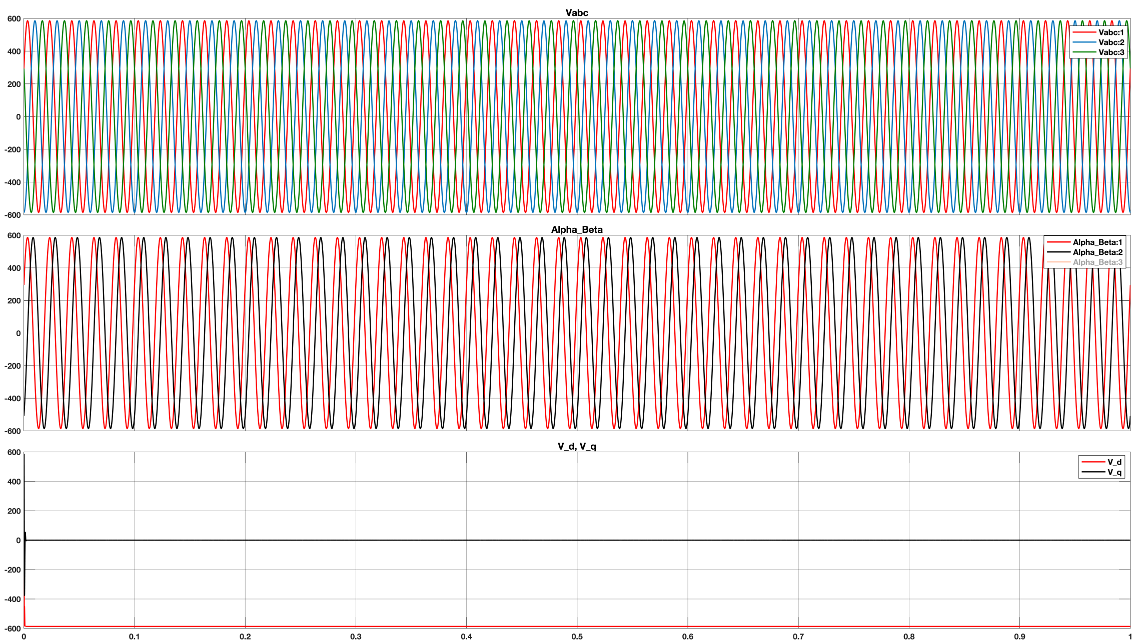


Figure 4.4: G2V Voltage Waveforms

The Figure 4.5 represents the 3ϕ, quantities such as voltage and current when the OCEPS is operating under the mode of G2V.

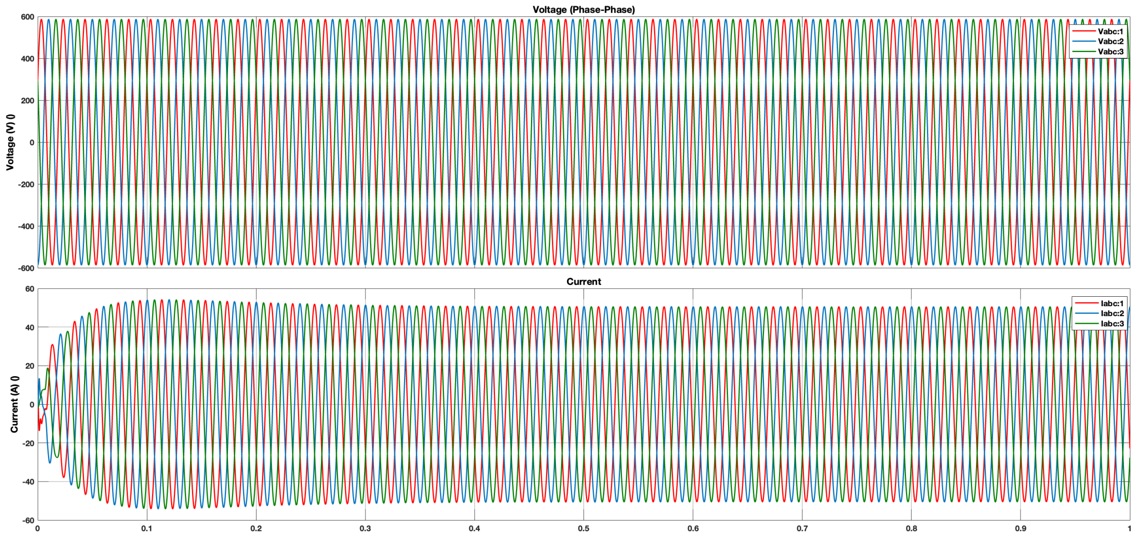


Figure 4.5: G2V Three Phase Waveforms

The Figure 4.6 represents the zoomed 3ϕ, quantities such as voltage and current when the OCEPS is operating under the mode of G2V where the voltage and current is not in phase depicted there is a transfer of power from the grid to the vehicle.

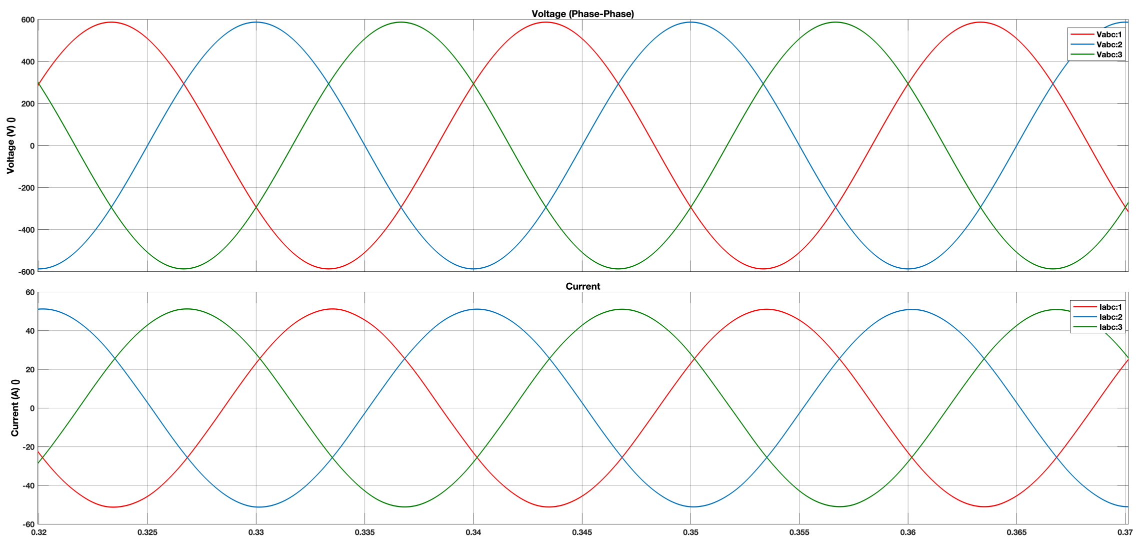


Figure 4.6: G2V Three Phase Waveforms Zoomed

The Figure 4.7 represents the appropriate transformations of current between 3ϕ to dq framework when the OCEPS is operating under the mode of G2V.

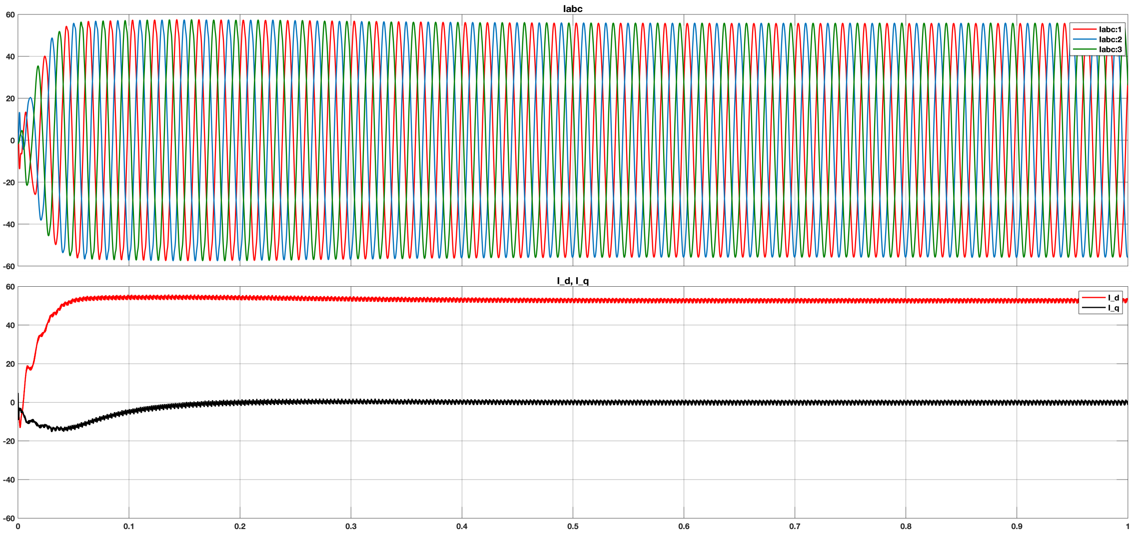


Figure 4.7: G2V Current Waveforms

Since the OCEPS is working under the control of Grid-to-Vehicle, the battery is under the mode of charging hence the State of Charge and terminal voltage of the battery increases as depicted in Figure 4.8.

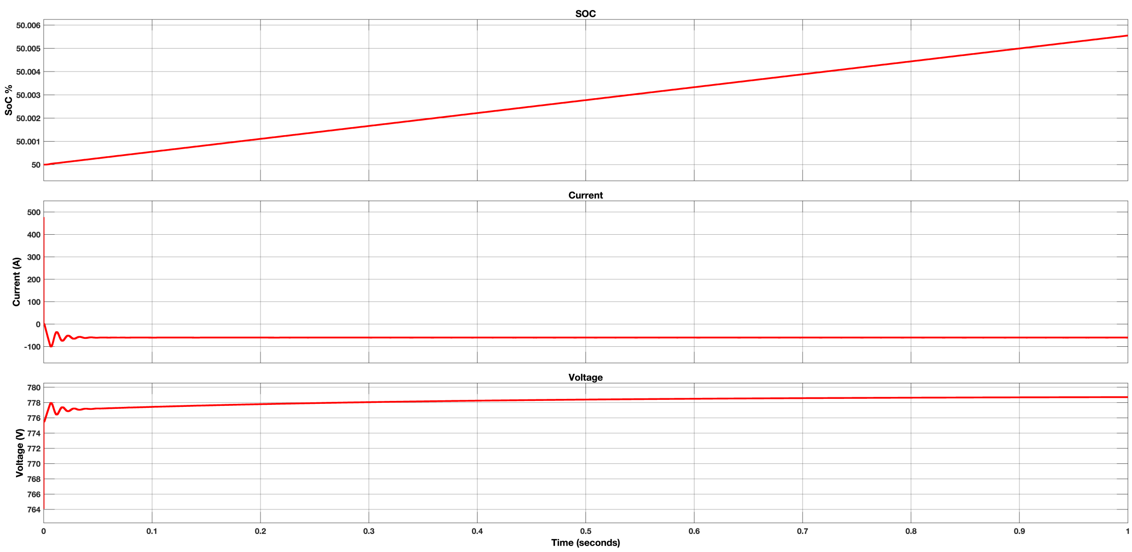


Figure 4.8: G2V Battery Operations

The Figure 4.9 represents the appropriate transformations between 3ϕ, Stationary and rotating frameworks when the OCEPS is operating under the mode of V2L.

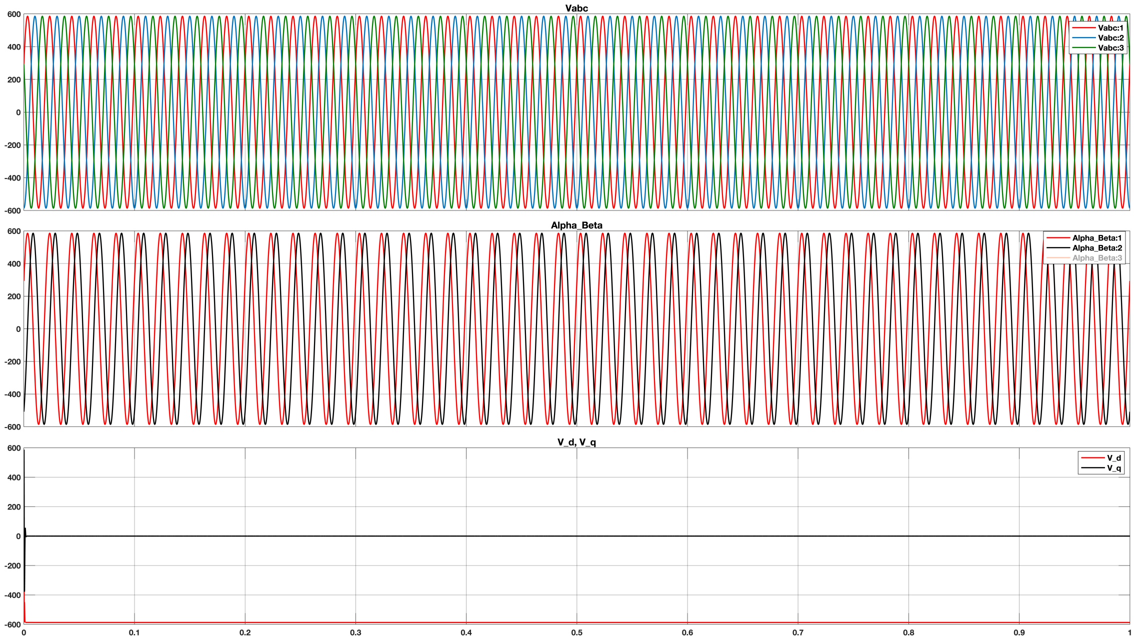


Figure 4.9: V2L Voltage Waveforms

The Figure 4.10 represents the 3ϕ, quantities such as voltage and current when the OCEPS is operating under the mode of V2L.

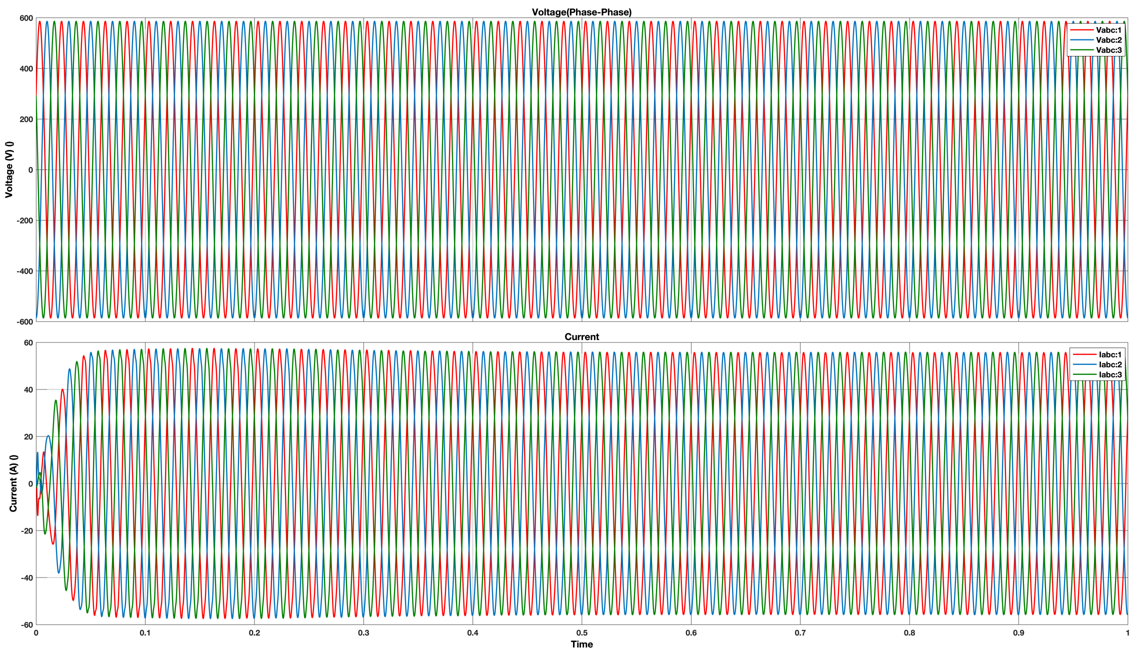


Figure 4.10: V2L Three Phase Waveforms

The Figure 4.11 represents the zoomed 3ϕ, quantities such as voltage and current when the OCEPS is operating under the mode of V2L where the voltage and current is in phase depicted there is a transfer of power from the vehicle to the load.

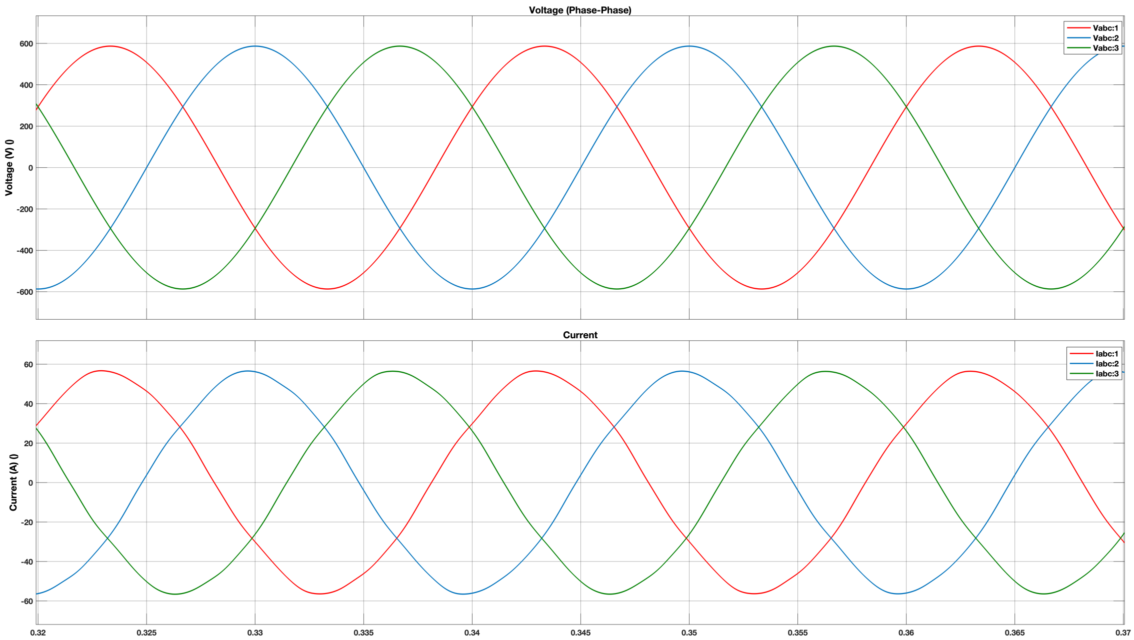


Figure 4.11: V2L Three Phase Waveforms Zoomed

The Figure 4.12 represents the appropriate transformations of current between 3ϕ to dq framework when the OCEPS is operating under the mode of V2L.

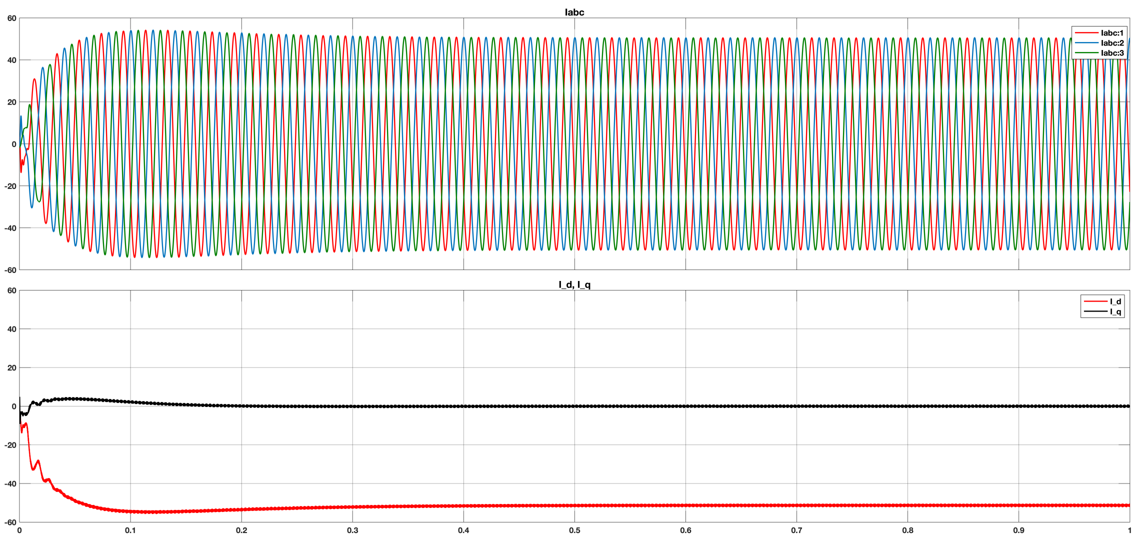


Figure 4.12: V2L Current Waveforms

Since the OCEPS is working under the control of Vehicle-to-Load, the battery is under the mode of discharging hence the State of Charge and terminal voltage of the battery decreases as depicted in Figure 4.13.

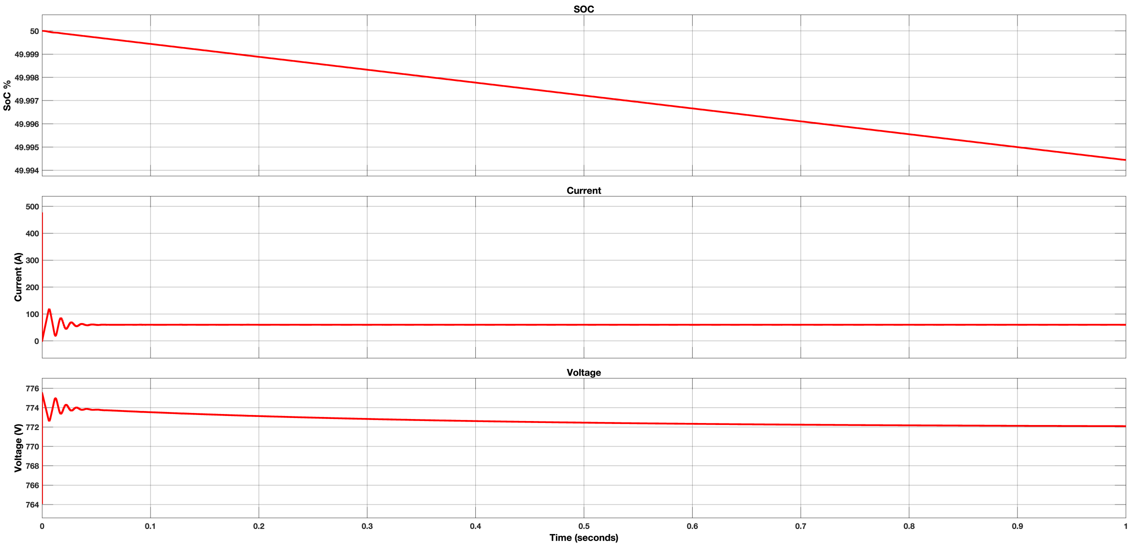


Figure 4.13: V2L Battery Operations

Any Power electronics must be safe under the set limits in terms of total harmonics distortion (THD). Both operations of V2L and G2V were subjected to harmonic analysis with the principle of Fast Fourier Transformation (FFT) as depicted in Figure 4.14. The standards set by IEEE denotes that the THD for these find of applications and ratings must be below 5%. Similarly the result from the Figure 4.15 depicts that the designed system has only 0.96% of THD, which is way under the recommended limit.

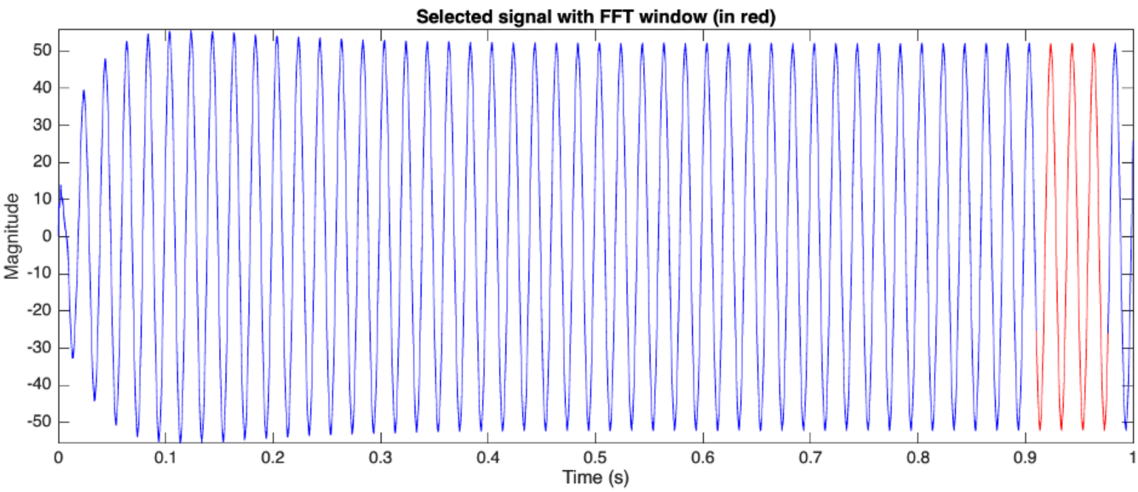


Figure 4.14: Selected Window for FFT Analysis

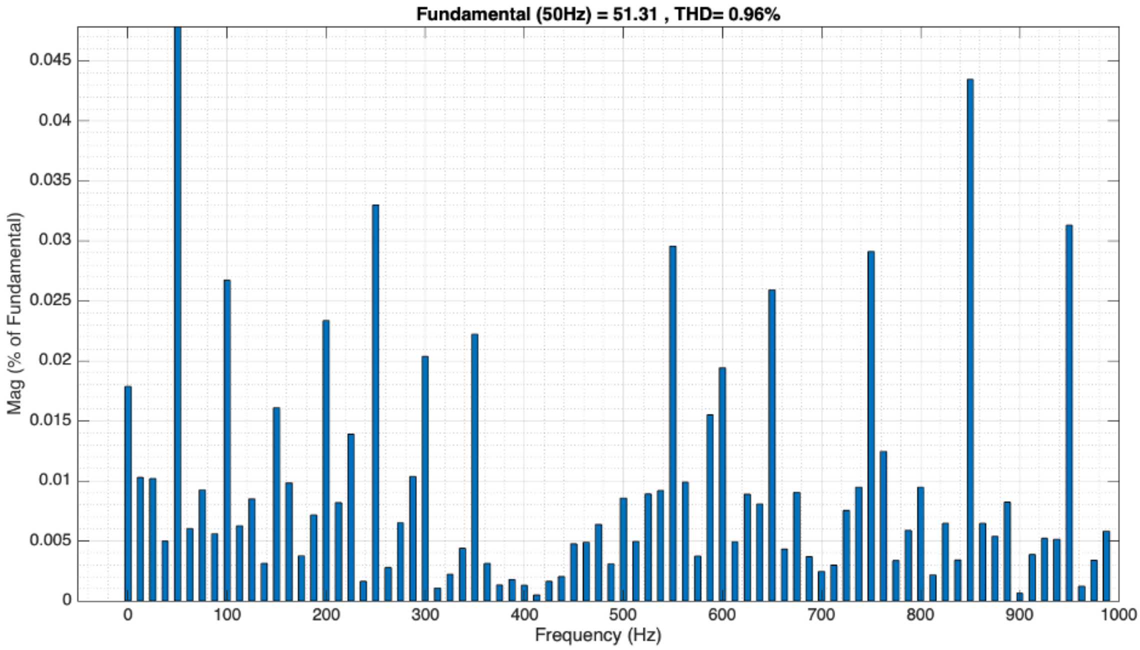


Figure 4.15: THD

4.5 Lifetime Calculation

As discussed previously in the working of a MOSFET, we tried to simulate and calculate the losses and thermal of a SiC MOSFET. Initally the existing custom module was simulated and analysed for performance benching and found that they had thermal issues and comparative lower lifetime by using Wohler's and Miners rules.

Wohler's rule is based on rainflow algorithm which calculates the fatigue of the component in the overall lifetime. Subsequently convert the uniaxial loading of varying stress into an constant amplitude of stress. Hence rainflow algorithm is named after subsequent flow of rain in rise and fall in the roof.

On the other hand Miner's rule helps us to calculate the accumulated damage **D** as the percentage of total finite life fatigue a component can handle before failure. A broken component has a **D** value more than 1, else it is less than 1.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_{fi}} = 1$$

Where N_{fi} is the Number of cycles before failure and N_i is the number of cycles at a given stress load.

$$T_{life} = \frac{T}{D}$$

Where **T** is the time cycle of load.

Using a simplified calculation of lifetime, Modified Coffin-Manson model can be implemented with the curves depicted in Figure 4.16 and using the below equation.

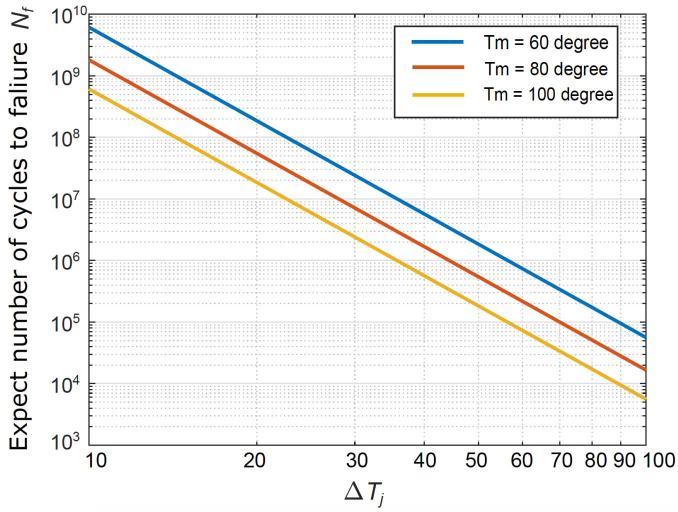


Figure 4.16: Wohler Curve

$$N_f = A\Delta T_j^{\alpha} e^{(\frac{E_a}{k_B T_m})}$$

Where ΔT_j is referred as difference in junction temperature, **A** and α are model parameters. E_a is the activation energy, K_B is the Boltzmann-constant and T_m is the average temperature in Kelvin.

	A	α	E_a	k_B
Value	302500	-5.039	9.89×10^{-20} J	$1.38 \times 10^{-23} JK^{-1}$

Table 4.2: Values of Modified Coffin Manson Lifetime Model

The reliability of a component is mainly dependant on operating hours, rise and fall in temperature during turn on/off, mean temperature of the module and coolant temperature.

When the existing custom module was subject to tests the value for the parameters were computed as in Table 4.3.

	N	ΔT_j ($^\circ C$)	T_m ($^\circ C$)	Switching Frequency (KHz)
Value	62.5	5	95	30
	0.5	62.5	66	30

Table 4.3: Module Test Parameter

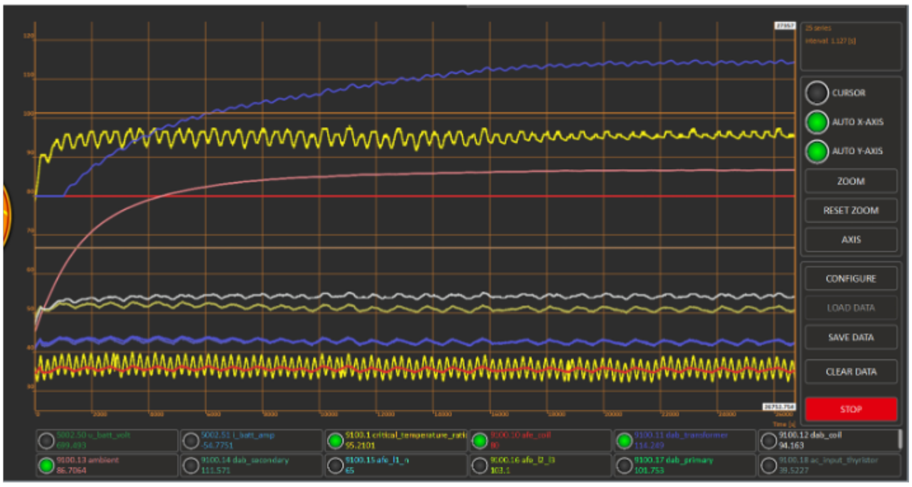


Figure 4.17: Module test Parameters (Credits Volvo GTT)

$$D_1 = \frac{N_1}{N_{fi}} = \frac{0.625 \times 30000 \times 26000}{302500 \times 5^{-5.039} \times e^{\left(\frac{9.89 \times 10^{-20}}{1.38 \times 10^{-23} \times (95+273)}\right)}} = 0.01869$$

$$Lifetime = \frac{t}{D} = \frac{26000}{0.01869} = 386 \ \ hours$$

Considering the truck uses the Module for 4.5 hours everyday.

$$Lifetime = \frac{386}{4.5} = 86 \ \ days$$

The simulation uses an acceleration factor of 1 day is equivalent to 1 week. Hence the lifetime is approximately 1.66 years. Considering a 90% reliability factor, the Mean Time To Failure (MTTF) is

$$MTTF = \frac{Lifetime}{log(2)} = \frac{1.66}{log(2)} = 5.51 \ \ years$$

Manufacturer	Topology	Model Number	Cost (SEK)	Peak Temperature (Celcius)	No of Modules Required	Total Cost (SEK)	Losses (Watts)	Efficiency	Remarks
Wolfspeed	Three Phase 2-Level AFE	CAB016M12FM3	1535	106	3	4605	384	99.10	Fully Controlled
		CAB011M12FM3	1826	105	3	5478	373	99.13	Fully Controlled
Semikron Danfoss	B6C	SKDT 145/12	1565	79	1	1565	243	99.43	Fully Controlled
	B6H	SK70DH12	515	70	1	515	145	99.66	Semi Controlled
	B6U	SK95D12	742	72	1	742	145	99.66	Uncontrolled
	B12US	SK80D12F	400	80	2	800	874	97.96	Uncontrolled
Infenion	B6U	DZ600N	2771	27	3	8313	288	99.33	Uncontrolled
		DD89N	1424	43	3	4272	339	99.21	Uncontrolled
		DD710N16K	4050	27	3	12150	300	99.30	Uncontrolled
		DD600N	3897	27	3	11691	288	99.33	Uncontrolled
		DD380N16K	2152	29	3	6456	291	99.32	Uncontrolled
		DD350N	2475	30	3	7425	291	99.32	Uncontrolled
		DD260N	2230	30	3	6690	290	99.31	Uncontrolled
		DD171N	1950	33	3	5850	300	99.30	Uncontrolled
		DD104N	1565	40	3	4695	315	99.26	Uncontrolled
	M6C	TZ600N	3000	26	6	18000	342	99.20	Fully Controlled
		TZ500N	2750	26	6	16500	342	99.20	Fully Controlled
		TZ425N	2445	26	6	14670	342	99.20	Fully Controlled
	M3.2U	DZ600N	2771	26	6	16626	282	99.34	Fully Controlled
	M3.2C	TZ600N	3000	26	6	18000	342	99.20	Fully Controlled
		TZ500N	2750	26	6	16500	342	99.20	Fully Controlled
		TZ425N	2445	26	6	14670	342	99.20	Fully Controlled
	B6C	TT92N	1617	43	3	4851	384	99.10	Fully Controlled
		TT61N	1138	47	3	3414	378	99.12	Fully Controlled
		TT250N	2490	30	3	7470	318	99.26	Fully Controlled
		TT180N		32.5	3		342	99.20	Fully Controlled
		TT162N	1979	32.5	3	5937	342	99.20	Fully Controlled
		TT142N		33.5	3		366	99.14	Fully Controlled
		TT104N	1660	43	3	4980	378	99.12	Fully Controlled
		TT330N16KOF	2675	29.5	3	8025	315	99.26	Fully Controlled
		TT330N16AOF	2570	29.5	3	7710	315	99.26	Fully Controlled
		TT285N	2530	29.5	3	7590	315	99.26	Fully Controlled
		TT270N16KOF		29.5	3		315	99.26	Fully Controlled
		TT251N	2430	29.5	3	7290	315	99.26	Fully Controlled
		TT600N16KOF	4382	28	3	13146	309	99.28	Fully Controlled
		TT570N16KOF	4183	28	3	12549	309	99.28	Fully Controlled
		TT570N18KOF	4277	28	3	12831	309	99.28	Fully Controlled
		TT500N	3983	28	3	11949	330	99.23	Fully Controlled
		TT425N	3865	28	3	11595	345	99.19	Fully Controlled
		TZ600N	3000	27	6	18000	345	99.19	Fully Controlled
		TZ500N	2750	27	6	16500	345	99.19	Fully Controlled
		TZ425N	2445	27	6	14670	345	99.19	Fully Controlled
		TT820N16KOF	5031	27	3	15093	306	99.28	Fully Controlled
		TT780N18KOF	5157	27	3	15471	306	99.28	Fully Controlled

Table 4.4: Component Study of SiC MOSFET in OCEPS

5

Repurposing of OCEPS into Off-board DC charger

Considering that we have successfully modelled the On board electric power system for the truck and it has been working for around its MTTF. Still 90% of the installed OCEPS will be functional after the MTTF which can be repurposed into an off-board DC charger by eliminating the need for Noise Vibration and Harshness (NVH) testing.

The main purpose of this thesis is to make sure that maximum of the OCEPS is being re-used to reduce the e-waste by using the concept of circular economy and sustainability. Hence the existing OCEPS is considered as a base architecture upon which required components are added to make it as a functional Off-board DC charger to meet our requirement.

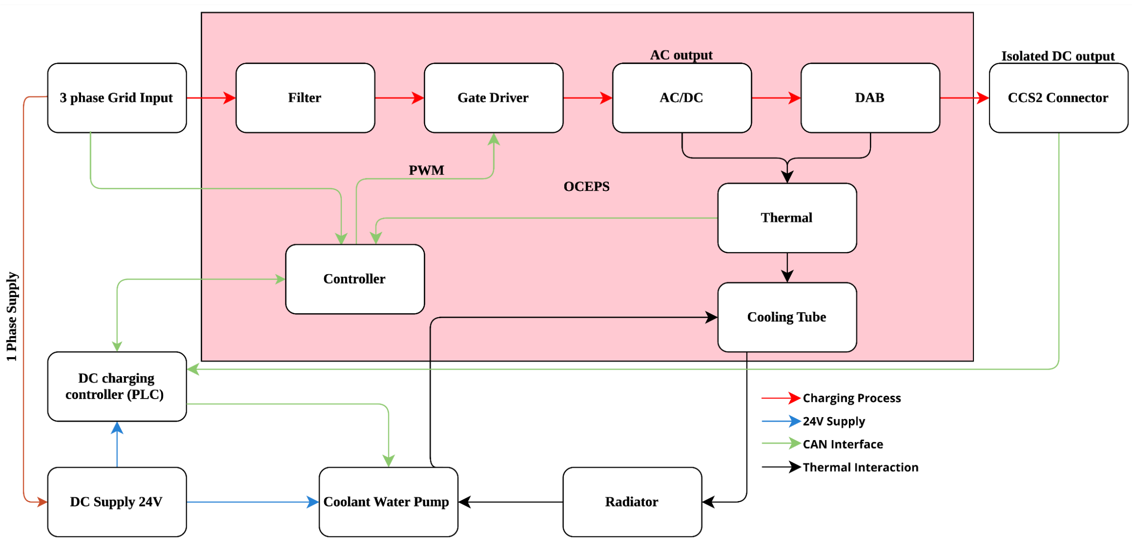


Figure 5.1: Repurposed OCEPS into a DC Charger

The primary applications of the repurposed OCEPS was explored and the results are as plotted in Figure 5.2. The sweet spot is present at around 40 - 43 KW on the other hand few application require more than the rating of OCEPS (43 KW), hence the repurposed model has to be easily scalable and compact as depicted in Figure 5.4.

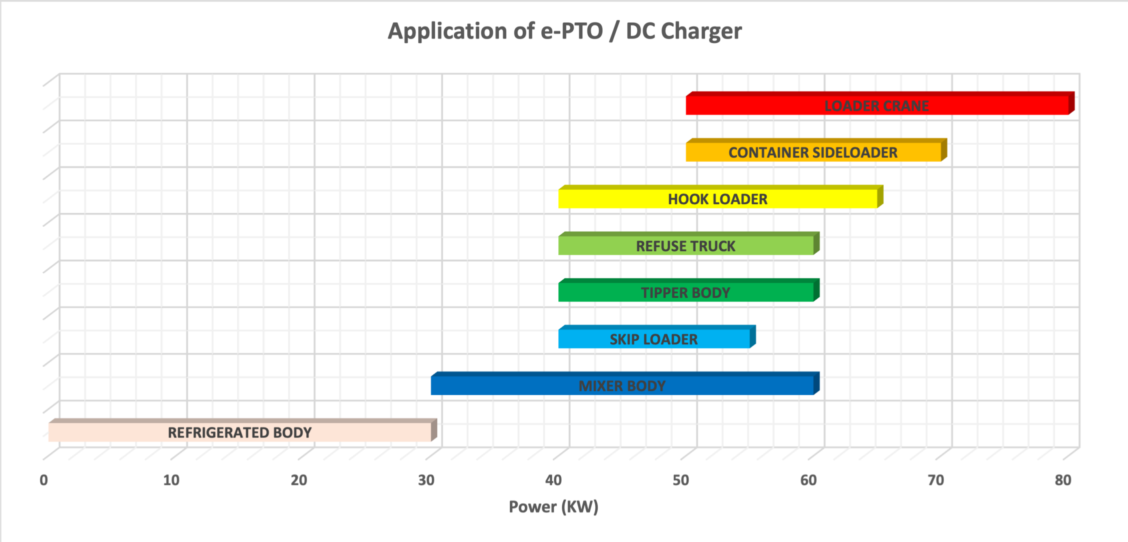


Figure 5.2: Application of Repurposed OCEPS

Contact Controller

An ideal contact controller must be able to communicate between vehicle and charger, support both AC and DC charging, it must comply with IEC 61851-23 standards and must be able to house various communication protocol such as TCP/IP, CAN, Server based, 4G etc.

DC Supply

A DIN rail DC supply capable of supplying 24V to power both controller and cooling pump. Similarly it must be in accordance with industrial standards.

Pump

The pump must support varied flow rate and must have low energy consumption and be easy to integrate.

Radiator

The radiator help in the reduction of coolant temperature through the process of convection.

Certain additional components as depicted in Figure 5.3

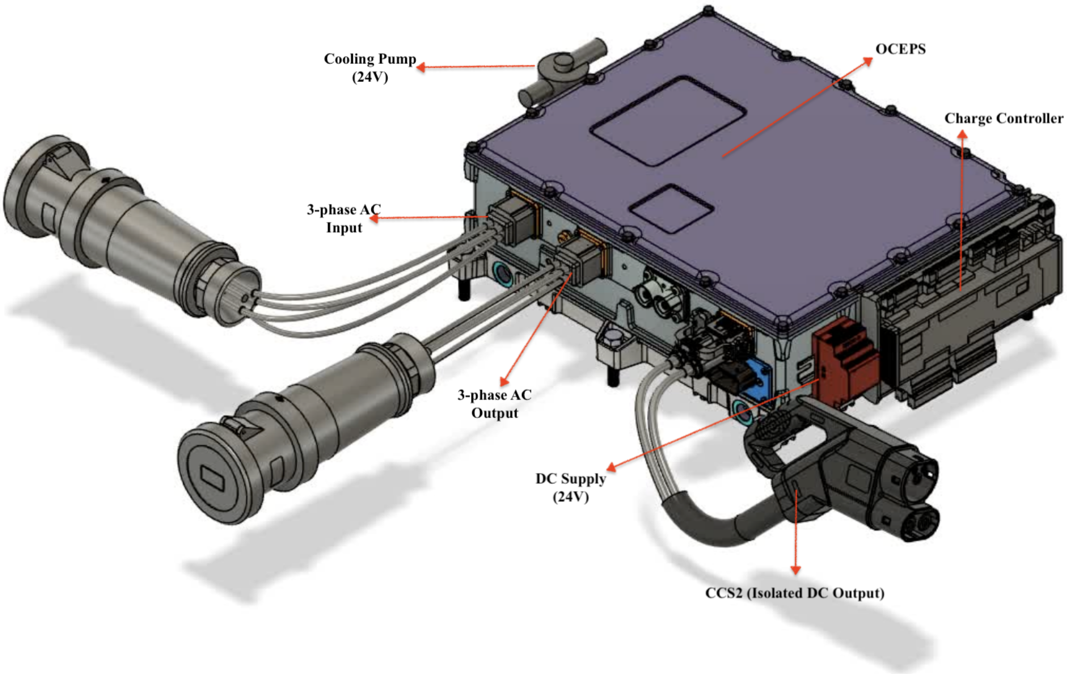


Figure 5.3: Repurposed OCEPS

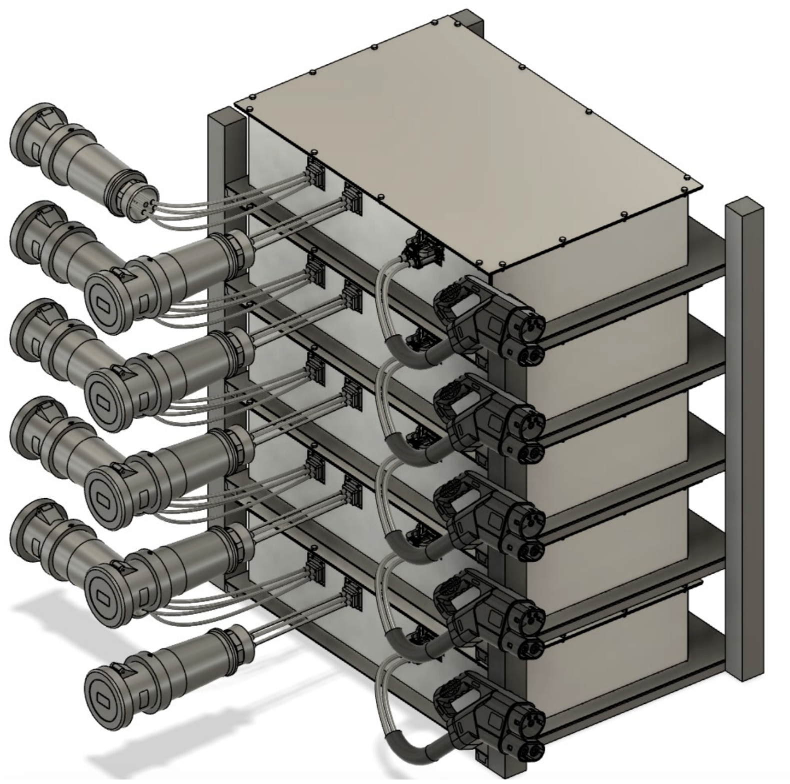


Figure 5.4: Scalable design of repurposed OCEPS

5.1 Feasibility Assessment

The aspect re-usability is always supported by values of sustainability and circular economy for a company to be able to scale up and make some profit.

Parts	Value (%)
OCEPS	40.42
EXTERNAL BODY	2.25
PLC COMMUNICATION	44.91
AC DC	1.20
PUMP	0.75
ASSEMBLY KIT	0.75
RADIATOR AND TUBING	1.95
ASSEMBLY	1.80
DISSASSEMBLY	2.69
TESTING	1.80
MISCELLANEOUS	1.50
TOTAL	100.00

Table 5.1: Value of Components (Repurposed OCEPS)

In previous chapter we have considered a reliability of 90% which can be directly repurposed into offboard DC charger and remaining 10% can be subjected to extra End of Life (EOL) testings in correspondence to reliability calculation as explained previously. Figure 5.5 provides an exploded view of the OCEPS.

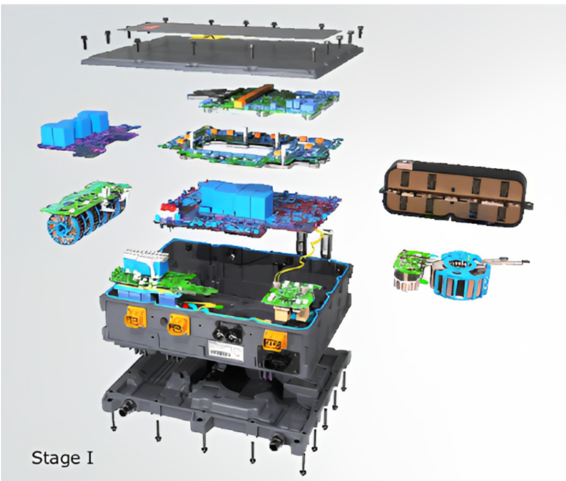


Figure 5.5: Exploded view of OCEPS (Credits Volvo GTT)

Considering the market analysis where we compared our proposed DC to other competitors in the similar power category, we found an interesting study tabulated in Table 5.2.

	EKO-ENERGETYKA	DESIGNWORK	HELIOX	KEMPOWER 1	KEMPOWER 2	PHIHONG	Proposed DC
Input Current (A)	80	63	63	63	63	60	63
Input voltage (V)	360 to 440	200 to 460	400	380 to 480	380 to 480	380 to 415	230 to 400
Input Power (kVA)	43	44	43	43.6	43.6	30	43.6
AC input	3 phase	3 phase	3 phase	3 phase	3 phase	3 Phase	3 Phase
Maximum Output Power (kW)	40	42	40	40	20(2 out)	30	43
Maximum Output Current (A)	67	120	67	60	60	50	59
Output Voltage (V)	150-950	250 to 1000	100 to 1000	920-1000	920-1000	150 to 950	500 to 850
Cooling Method	Air	Air	Air	Air	Air	Air (Fan Cooling)	Liquid
Dimensions (DxWxH)mm	600x860x1060	500x240x730	500x500x900	670x640x1220	670x640x1220	589x490x740	750x500x170
Weight (kg)	160	52	120	120	127	80	52
Cost ratio	1.32	1.41	1.63	1.96	2.02	1.04	1.00
Power Density (KW/Cost)	30.2883048	29.87303909	24.48166923	20.42831597	19.83918925	28.91824646	43
Power Density (kW/m^3)	73.13	479.45	177.77	76.46	76.46	138.35	722.68
Power Density (kW/kg)	0.25	0.807	0.33	0.33	0.314	0.375	0.827
Electrical safety protection	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Residual Current Protection	Yes	No	Yes	Yes	Yes	Yes	Yes
Overvoltage/Surge protection	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Over temperature	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EMC fulfillment	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 5.2: Market Analysis and Comparison

In Table 5.2 it is evident that the repurposed OCEPS as a DC charger is comparatively cheaper, compact in size and therefore has higher power density both in terms of cost and volume.

5.2 Business Model

Since it is much evident that we have potential in terms of re-usability and it has a competitive price in terms of cost compared to other competitors in the market, we have to develop a business case model which is viable to set up as a start-up company.

Parameter	**Salary (p.m) SEK**	**Annual (mil. SEK)**
47 Starting Employees	**37000**	**20.868**
3 Main Employees	**50000**	**1.8**
Total Salary		**22.668**
Investment		**10**
Total		**32.668**

Table 5.3: Business Case Model

As tabulated in above Table 5.3, let us consider a start-up company with 3 main founders and 47 employees. Assuming a starting salary for founders and employees be 37000 and 50000 SEK per month respectively and spending 10 million SEK in investment of equipment's and setting up a factory, the first year expenses rounds to 32.668 million SEK.

When subject to mass production the cost of manufacturing reduces when the quantity of charger produced is high. The cost can be formulated by the given formulae:

$$S = S_0(\frac{C}{C_0})^{\frac{1}{\beta}}$$

and

$$\beta = \frac{log r_p}{log 2}$$

where, S_0 is the energy production in Giga Watts (GW), C & C_0 is the initial cost, C_1 is the target cost and r_p is the progression ratio.

While substituting the values from the Table 5.4 we calculated the cost to production for a higher quantity as depicted in below Figure 5.6.

Parameter	Value
C_0	1.5534
C_1	1.3953
S_0	0.000043
r_p	0.85
α	0.3

Table 5.4: Scale Factor Parameters

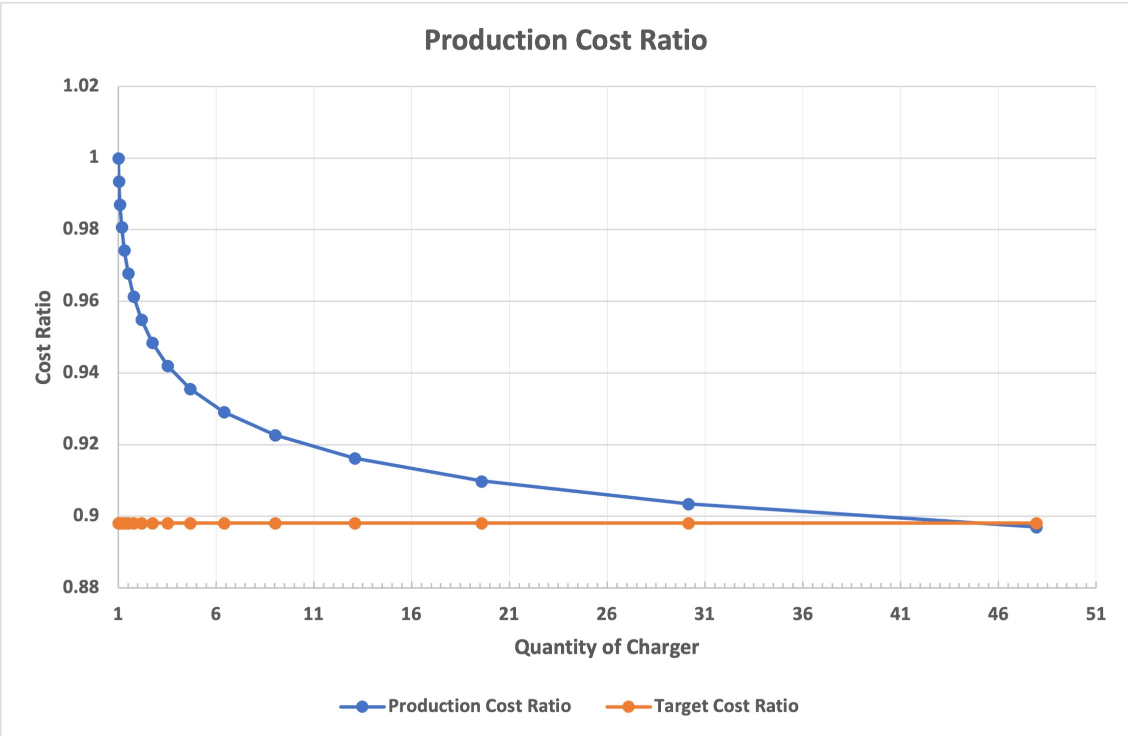


Figure 5.6: Production cost Vs Quantity

Assuming that the company would be able to re-purpose 1000, 5000 and 15000 units in first three years respectively as depicted in Table 5.5.

Time	Quantity	E.O.Y (mil.SEK)	Profit %
Year 1	1000	-3.6	-4.12
Year 2	5000	115.5	26.61
Year 3	15000	435.3	33.42

Table 5.5: Projected Sales Performance

The Table 5.5 provides a definite calculation that the re-purposing OCEPS has huge potential in terms of profit and providing a sustainable solution and reducing the generation of e-waste. It could open a niche market where this company would be the forerunners in the field of repurposing old On board charging solution to off board power supplies/ DC chargers.

6
Conclusion

In conclusion, the exploration of Second Life applications and lifetime analysis for repurposing electric vehicle components in off-board DC chargers presents a promising approach for advancing sustainable transportation and addressing the challenges of the evolving electric vehicle market. This thesis delved into the multifaceted benefits that Second Life applications offer, including extending the useful lifetime of EV components, reducing overall costs, and contributing to the integration of renewable energy sources into the grid through off-board charging solutions.

Through an in-depth analysis of various Second Life scenarios, it has become evident that repurposing used electric vehicle components for off-board DC chargers can significantly enhance the efficiency and viability of electric vehicles. By harnessing the residual capacity and functionality of retired EV components, such as power electronics and converters, the off-board chargers can help alleviate concerns about component disposal and contribute to a more circular and eco-friendly approach to EV technology.

Moreover, the implementation of Second Life applications and lifetime analysis for off-board DC chargers aligns seamlessly with global efforts to mitigate climate change and reduce carbon emissions. As the transportation sector continues its transition towards electrification, responsible resource management becomes paramount. Second Life applications not only contribute to a more sustainable transportation ecosystem but also promote research and innovation in repurposing technologies, energy storage systems, and grid integration for efficient charging solutions.

However, it is crucial to acknowledge the existing challenges and uncertainties associated with this emerging field. Technical complexities, regulatory frameworks, safety considerations, and economic viability all play pivotal roles in shaping the trajectory of Second Life applications for off-board DC chargers. As further research and development unfold, collaboration among academia, industry experts, and policymakers will be essential to navigate these challenges and fully realize the potential of repurposing EV components in off-board charging scenarios.

In summary, this thesis underscores the importance of reimagining EV component usage beyond their initial vehicular applications. By integrating retired electric vehicle components into off-board DC chargers, the automotive industry can address concerns about component disposal and unlock new opportunities for sustainable mobility and energy systems. As society advances towards a more sustainable future, Second Life applications and lifetime analysis for off-board DC chargers stand as a testament to human ingenuity and our ability to create innovative solutions that harmonize technological progress with environmental consciousness.

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7
Appendix

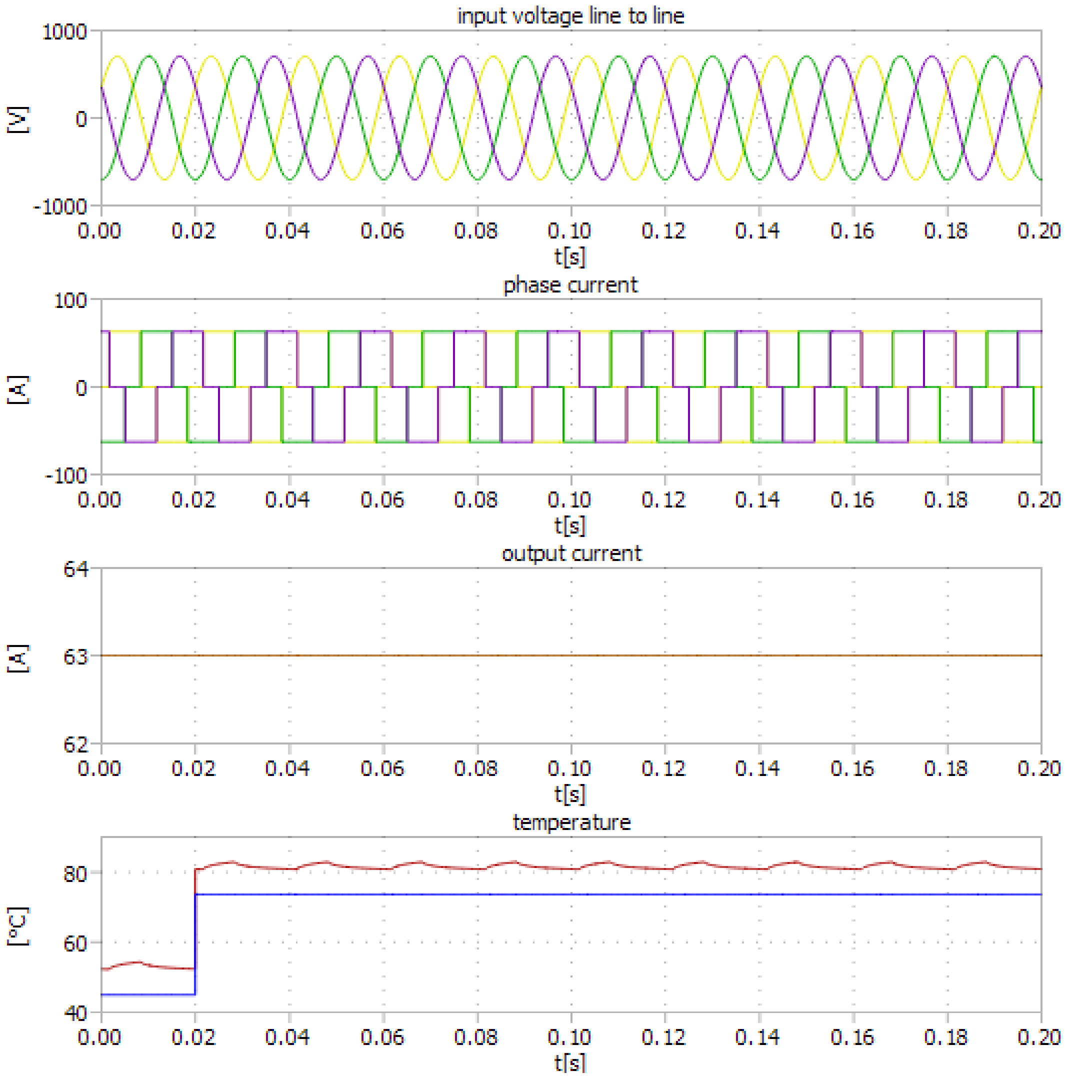


Figure 7.1: B6U - DD89N

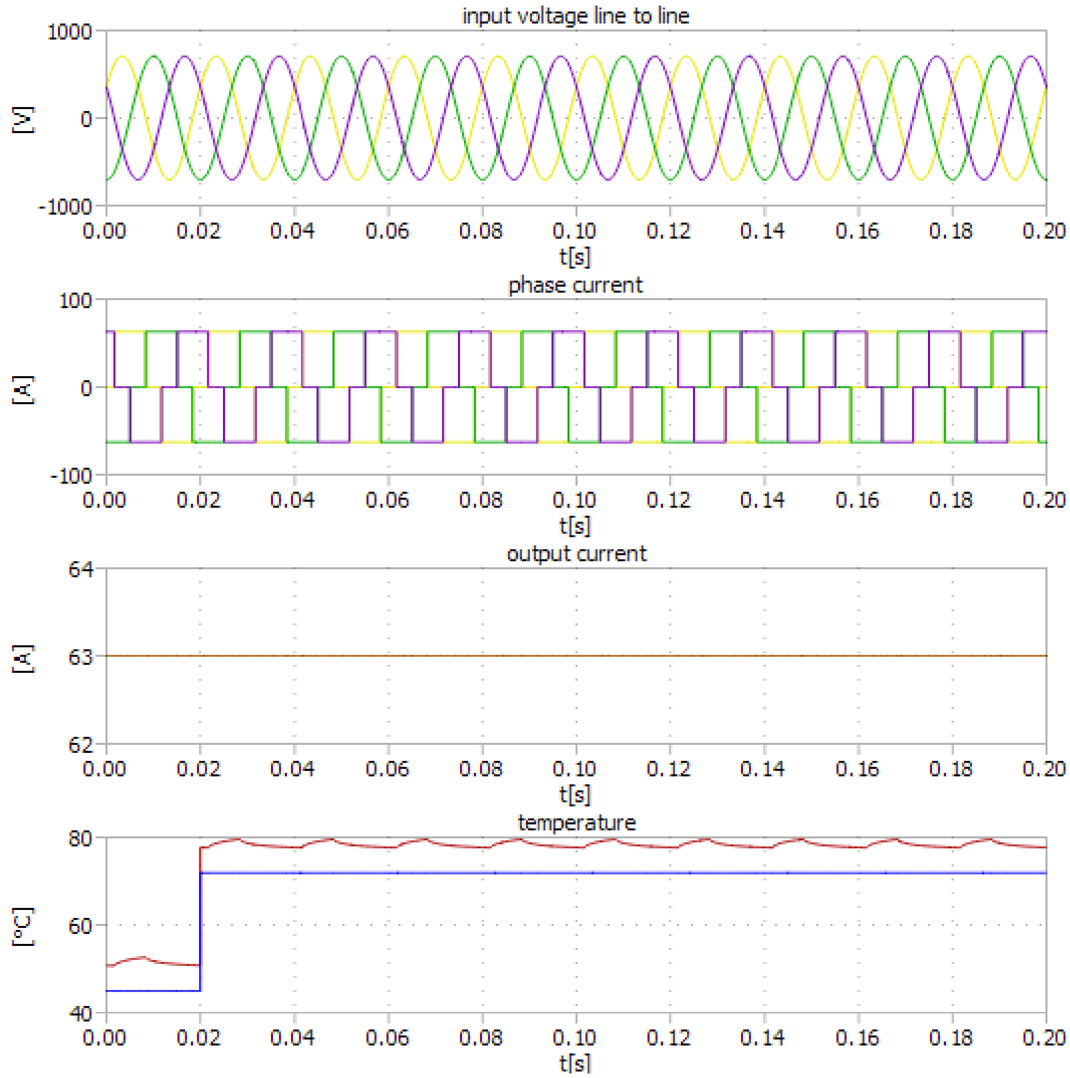


Figure 7.2: B6U - DD104N

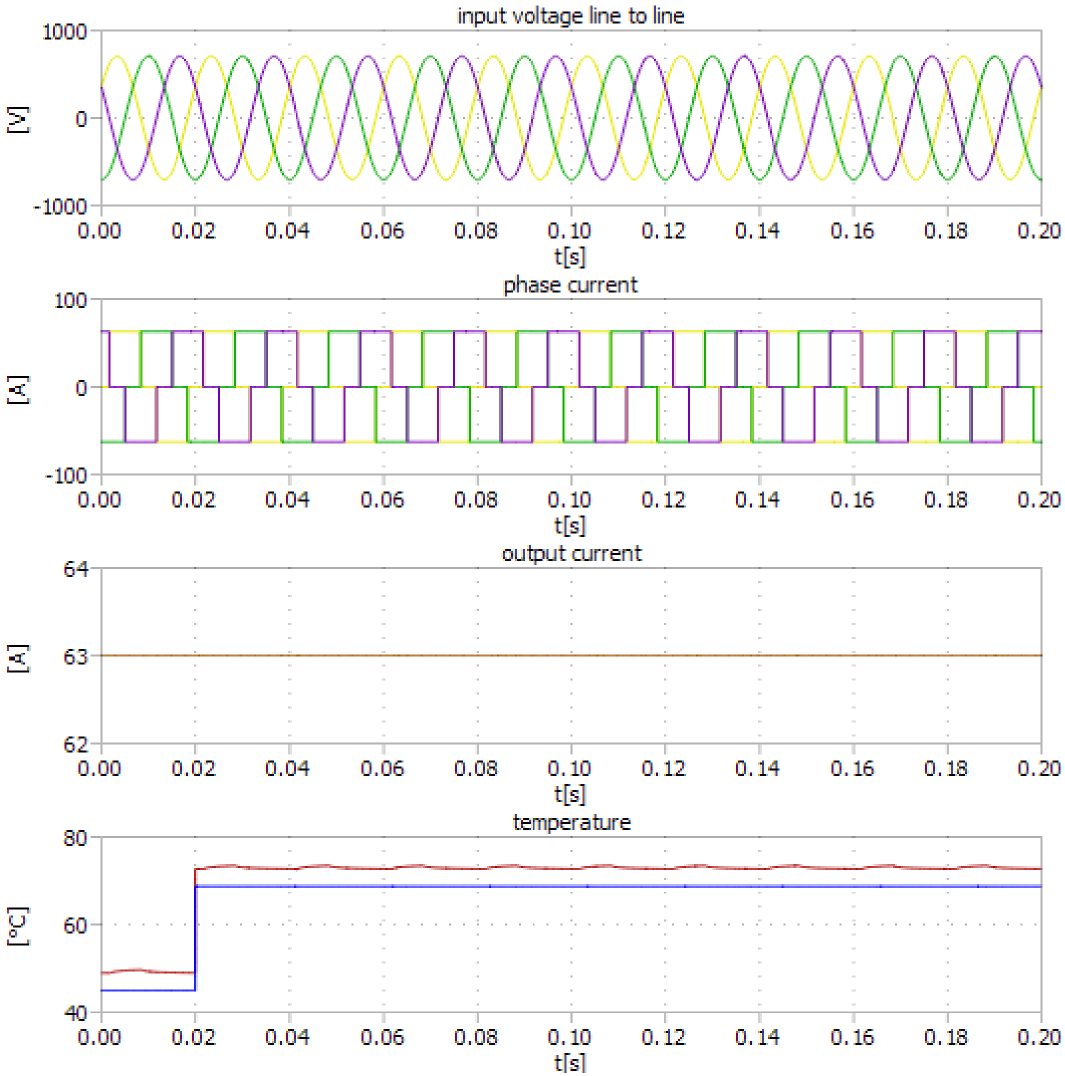
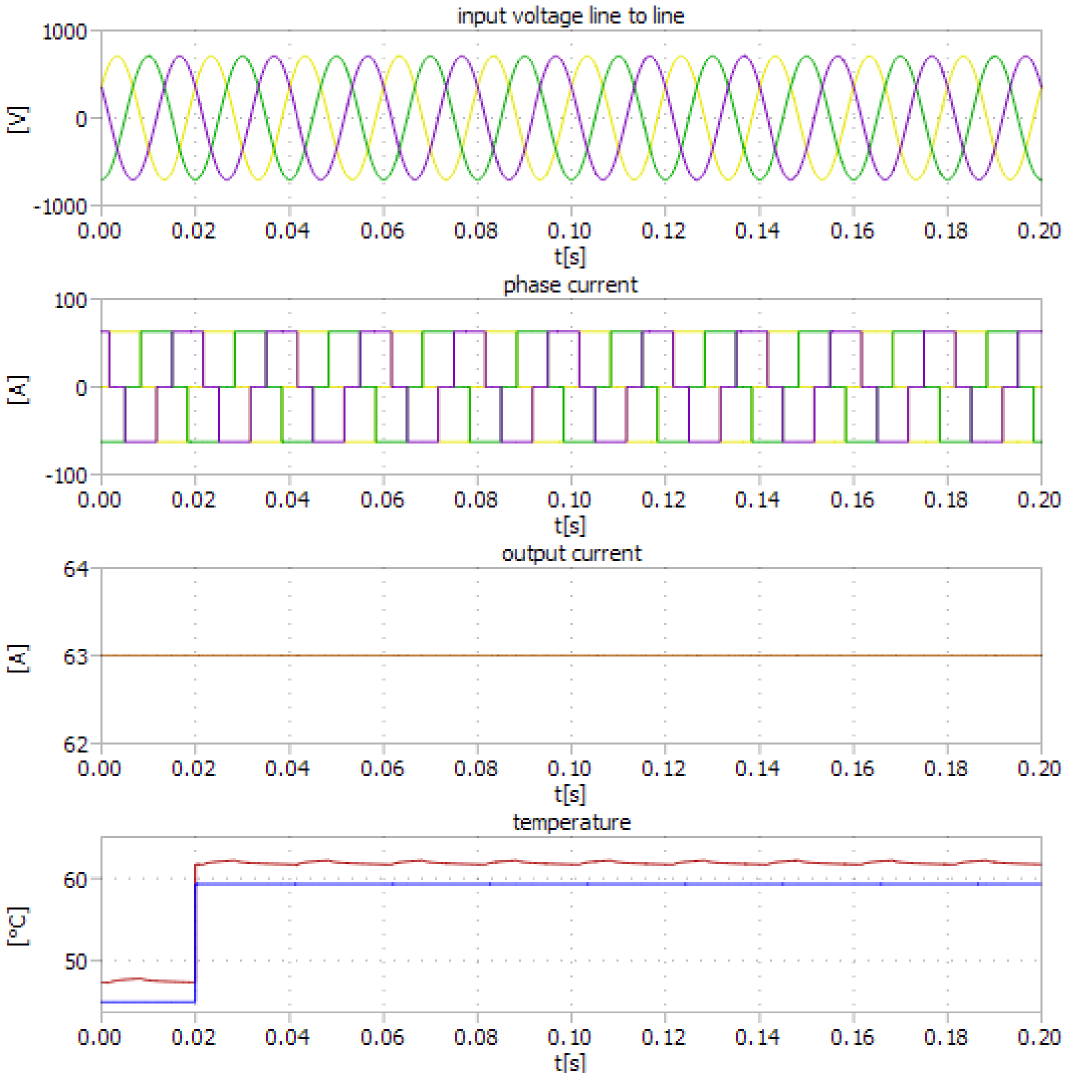


Figure 7.3: B6U - DD171N



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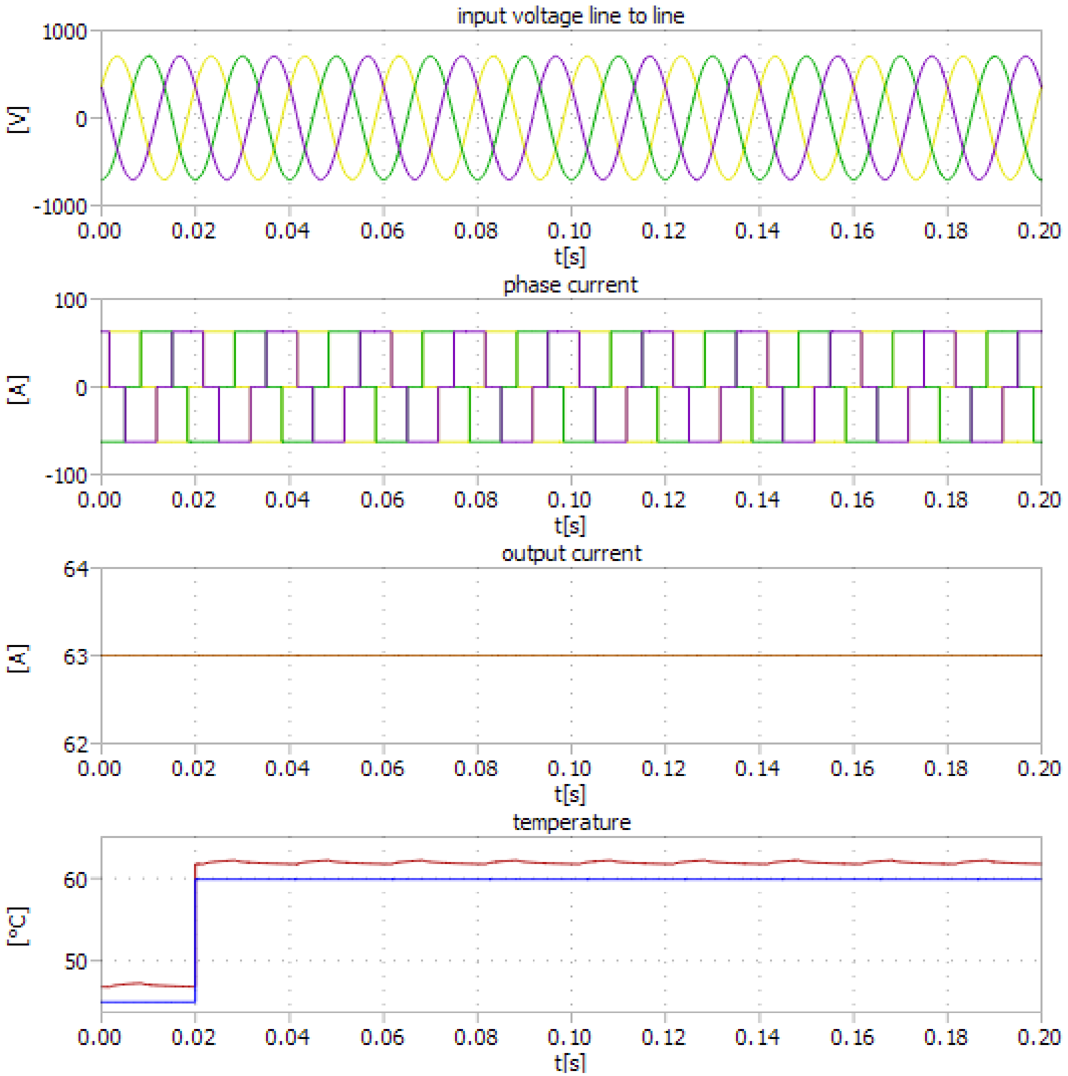


Figure 7.5: B6U - DD350N

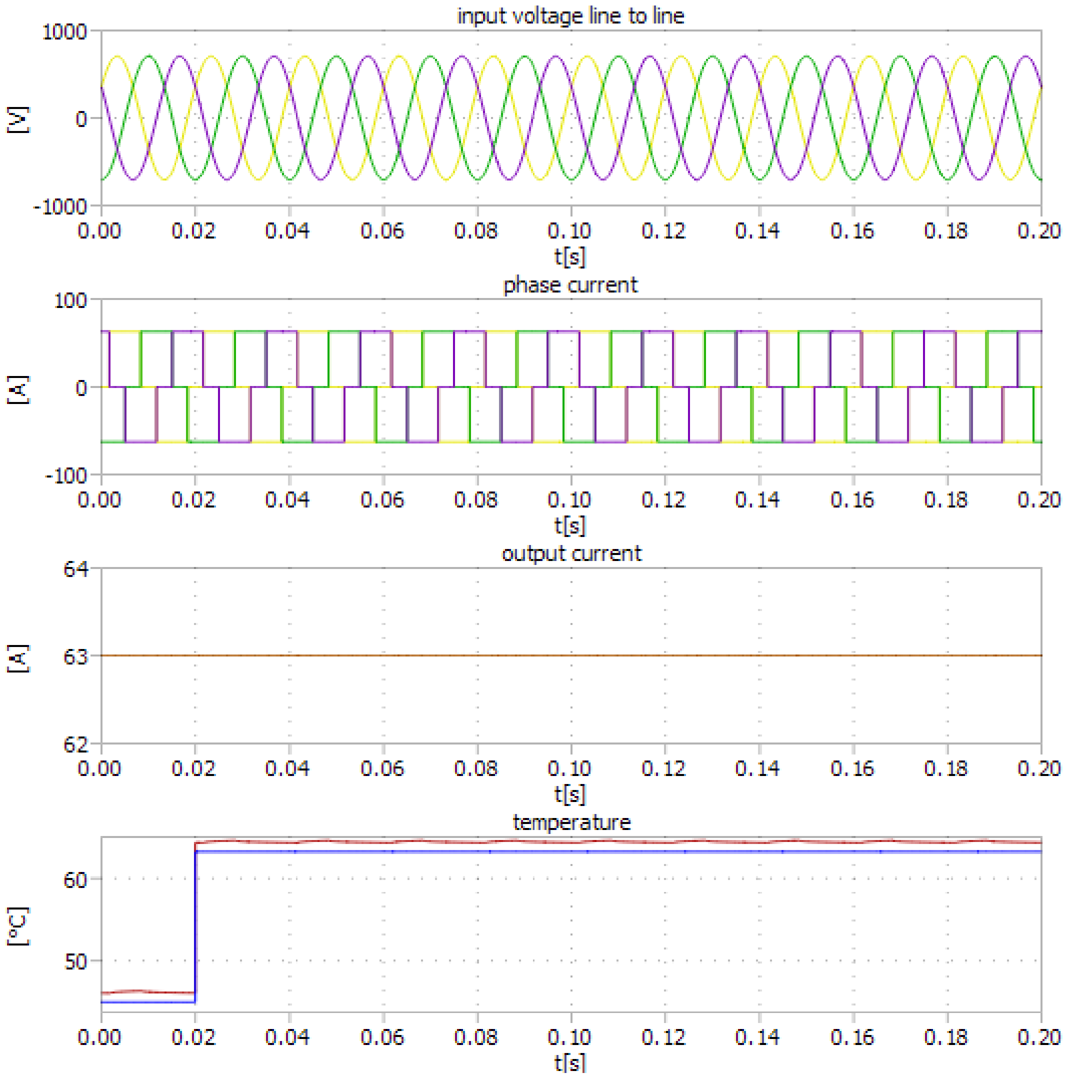
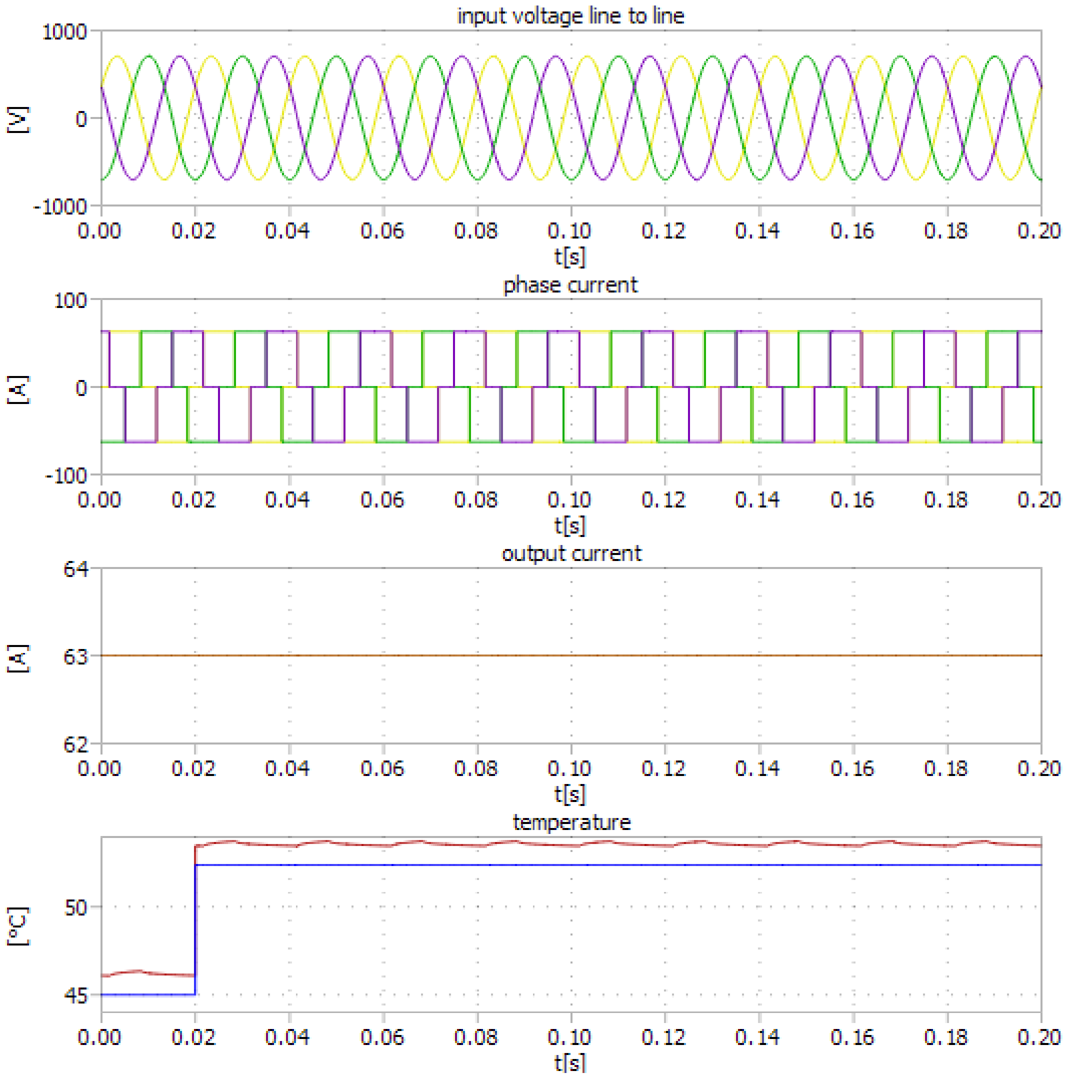


Figure 7.6: B6U - DD600N



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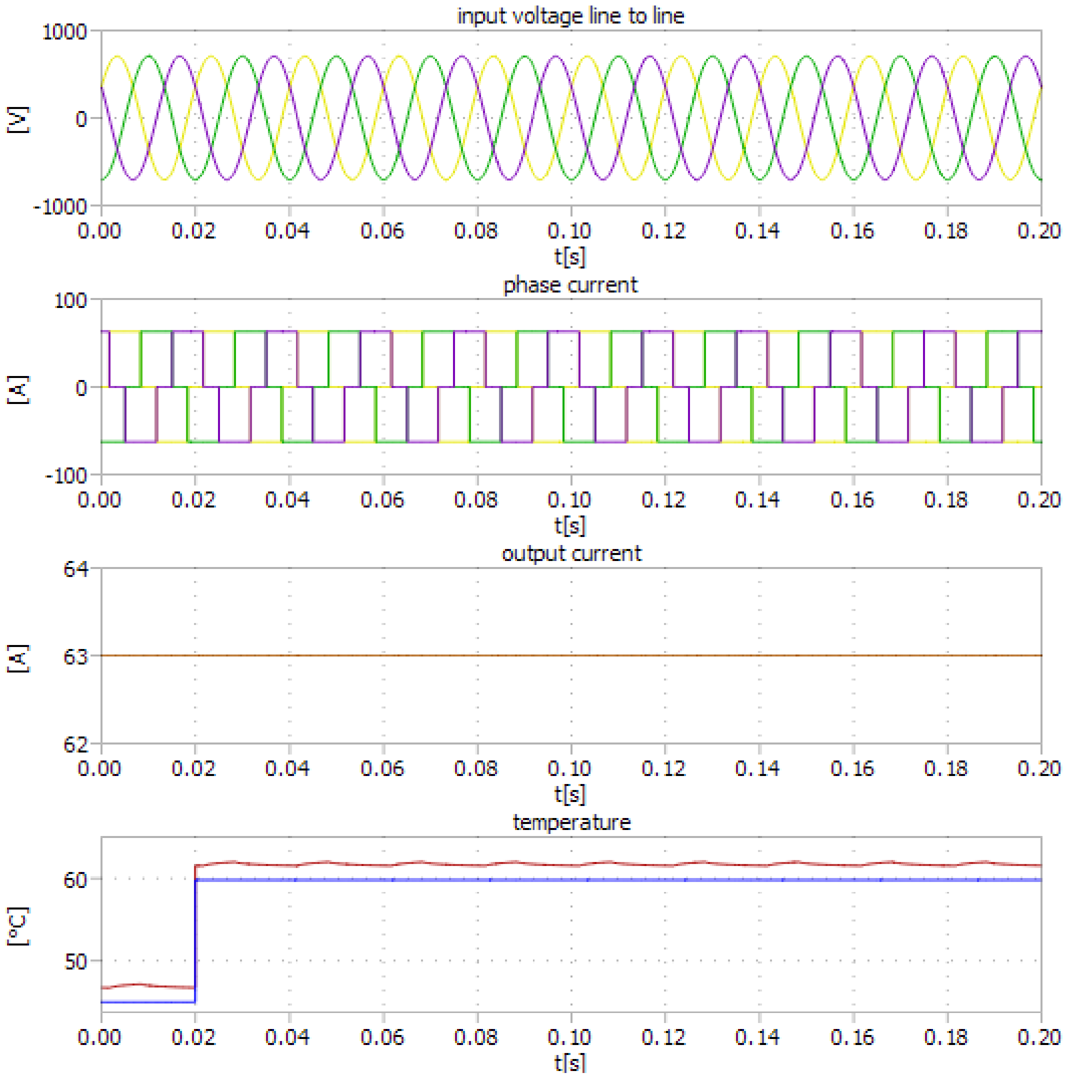


Figure 7.8: B6U - DD380N16K

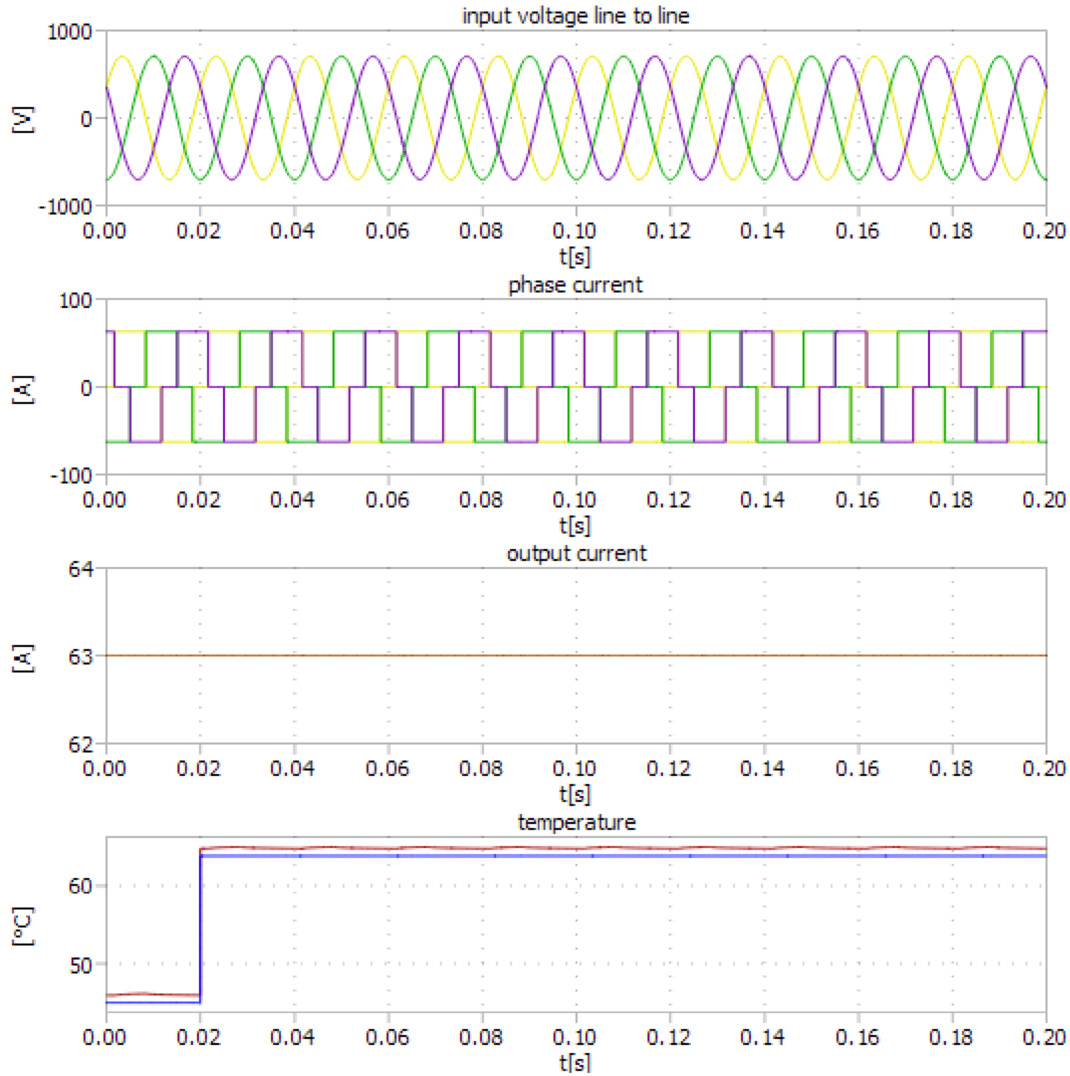


Figure 7.9: B6U - DD710N16K

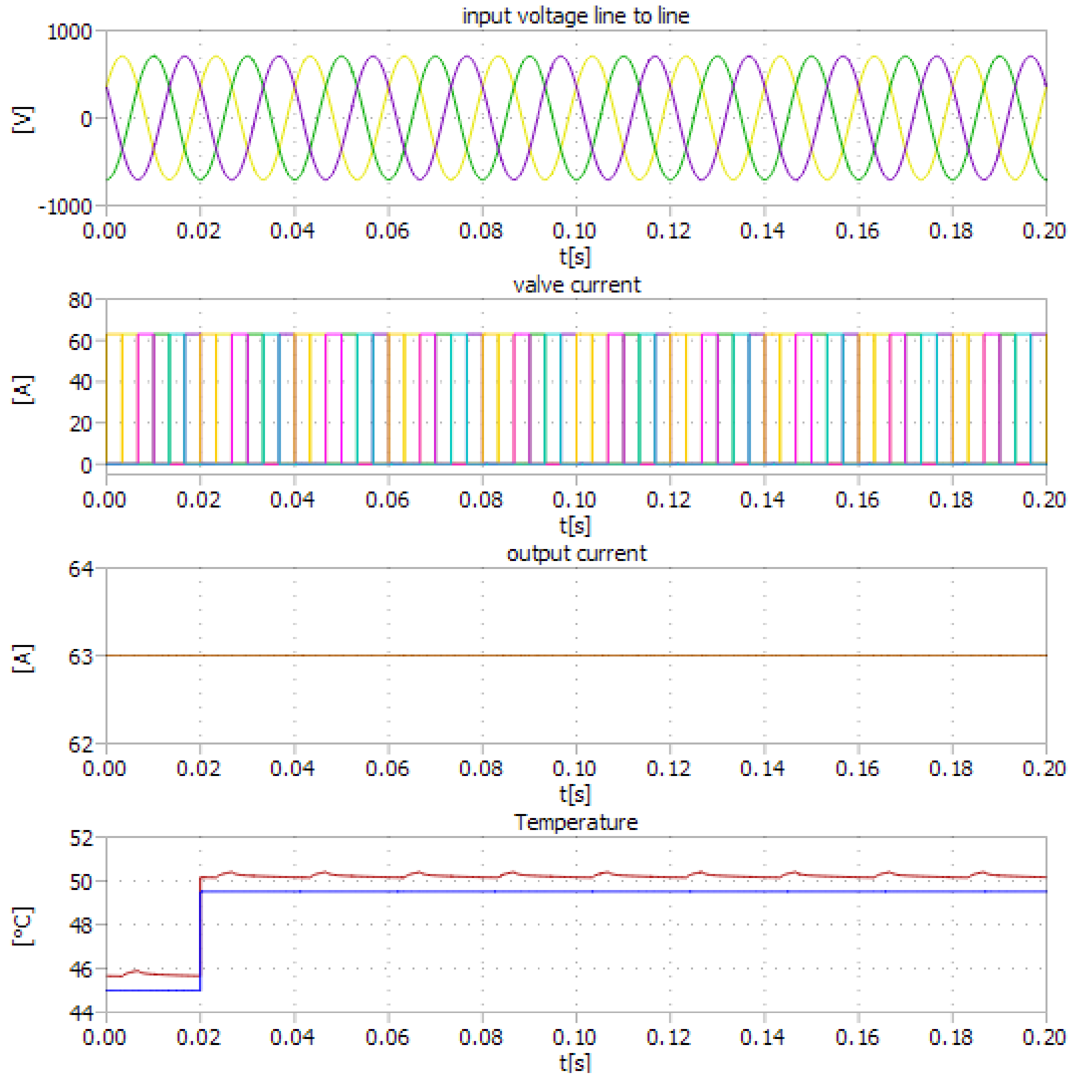
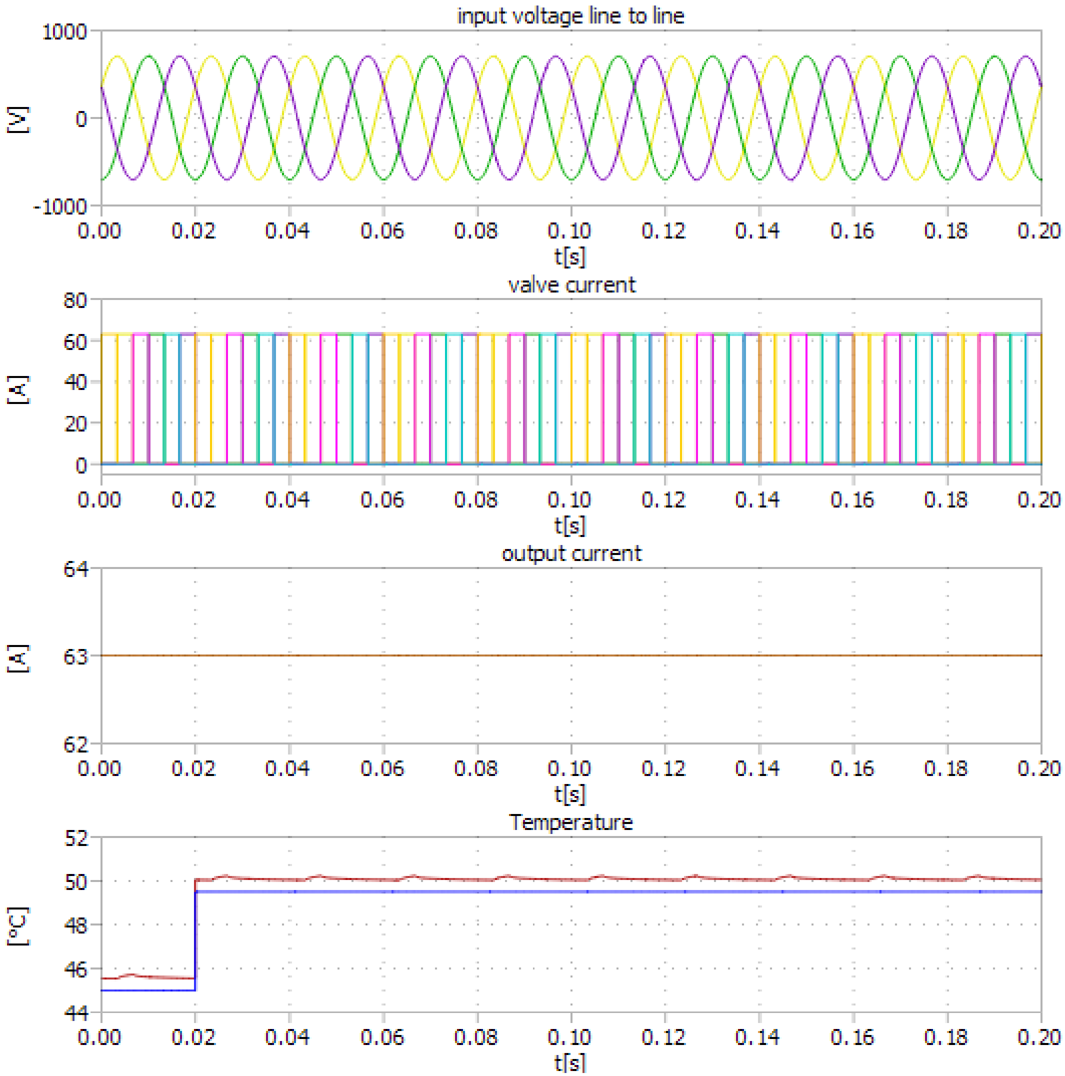


Figure 7.10: M6C - TZ425N



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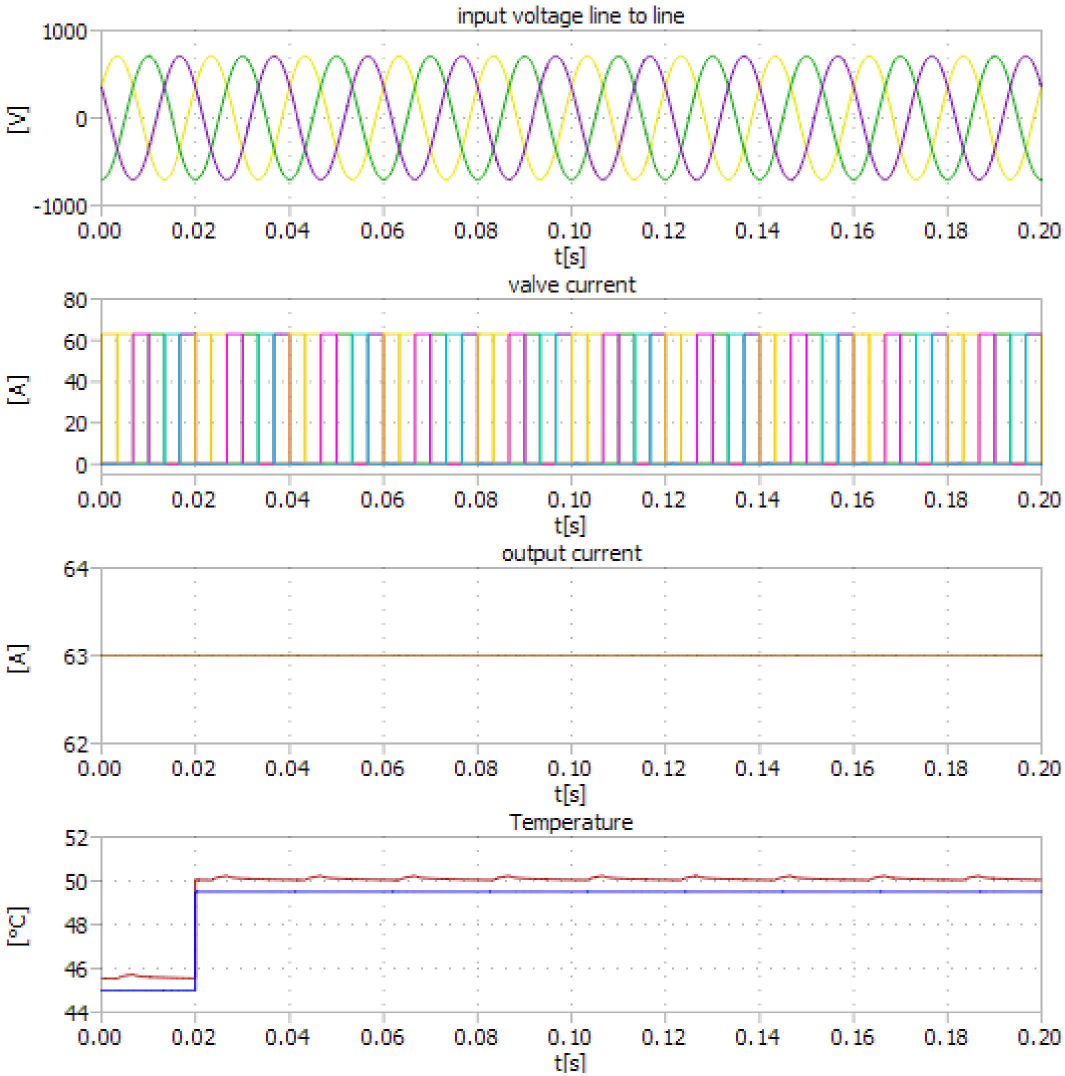

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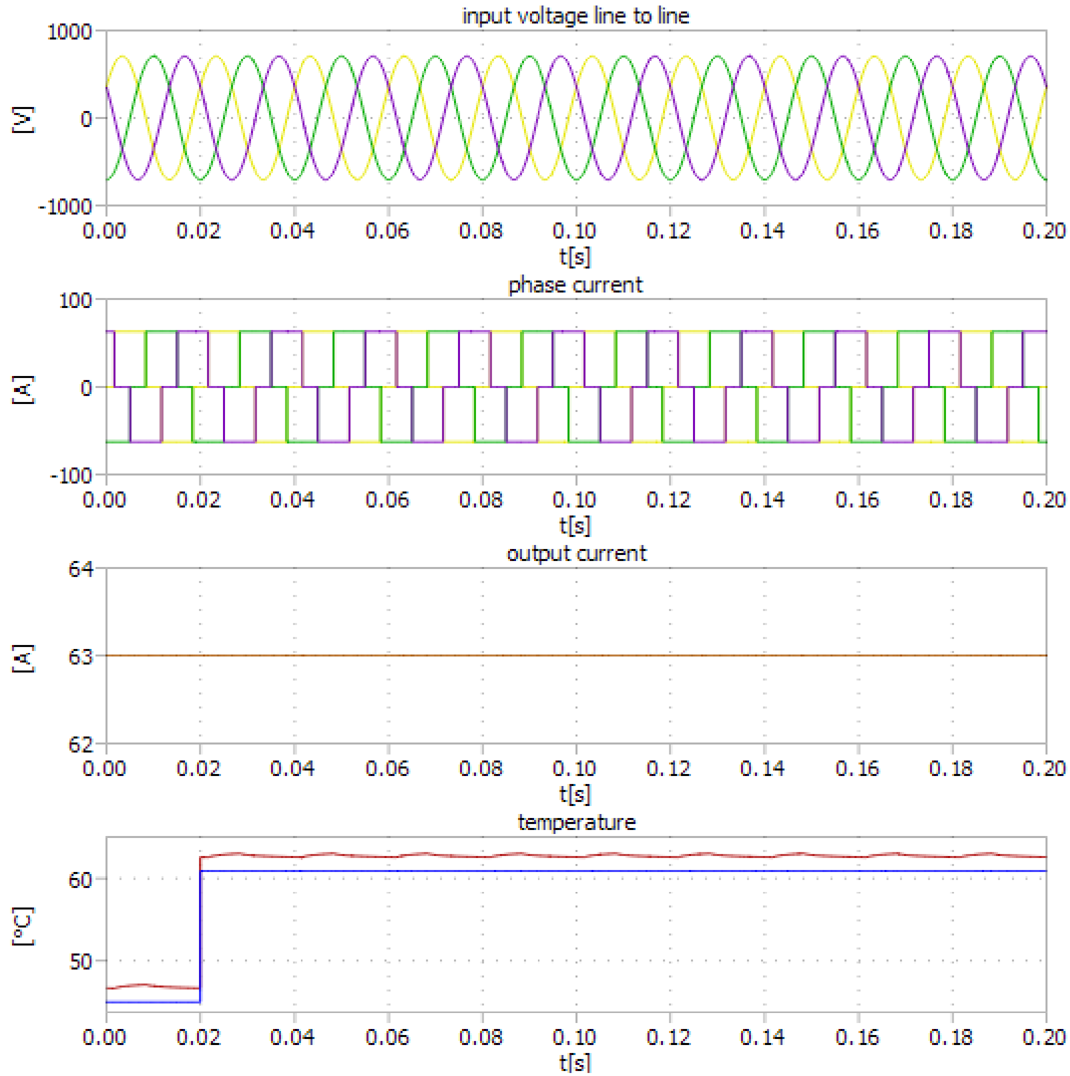

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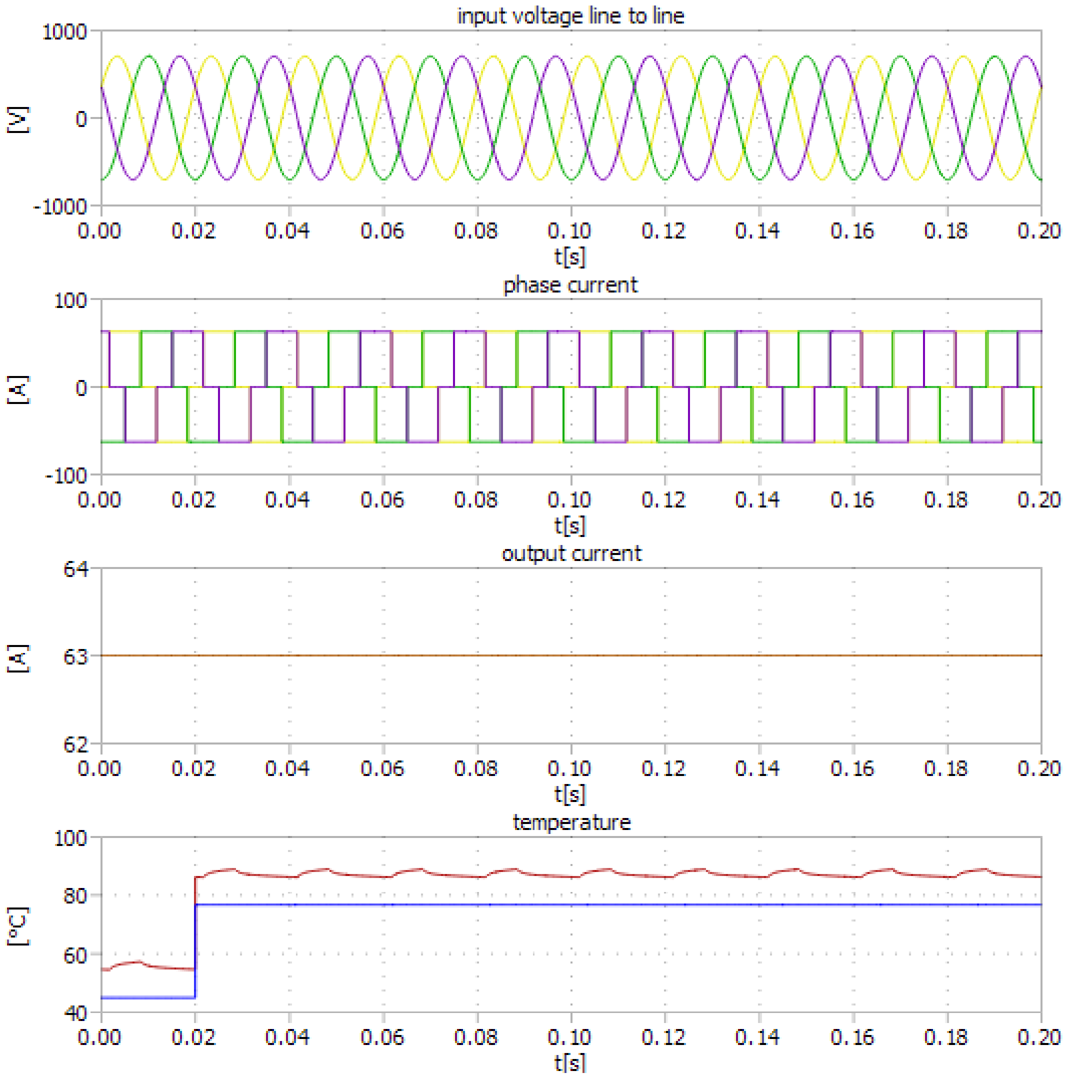

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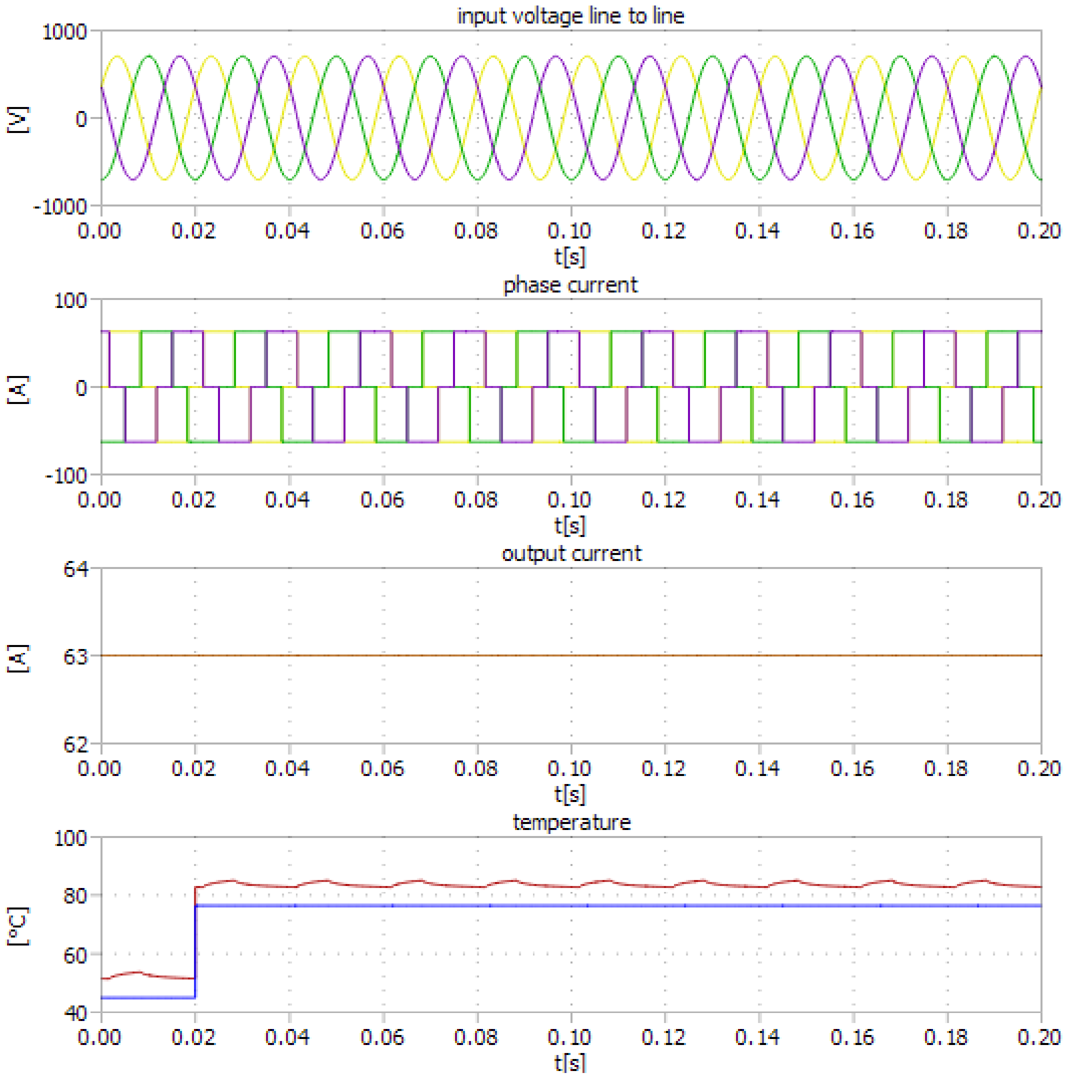

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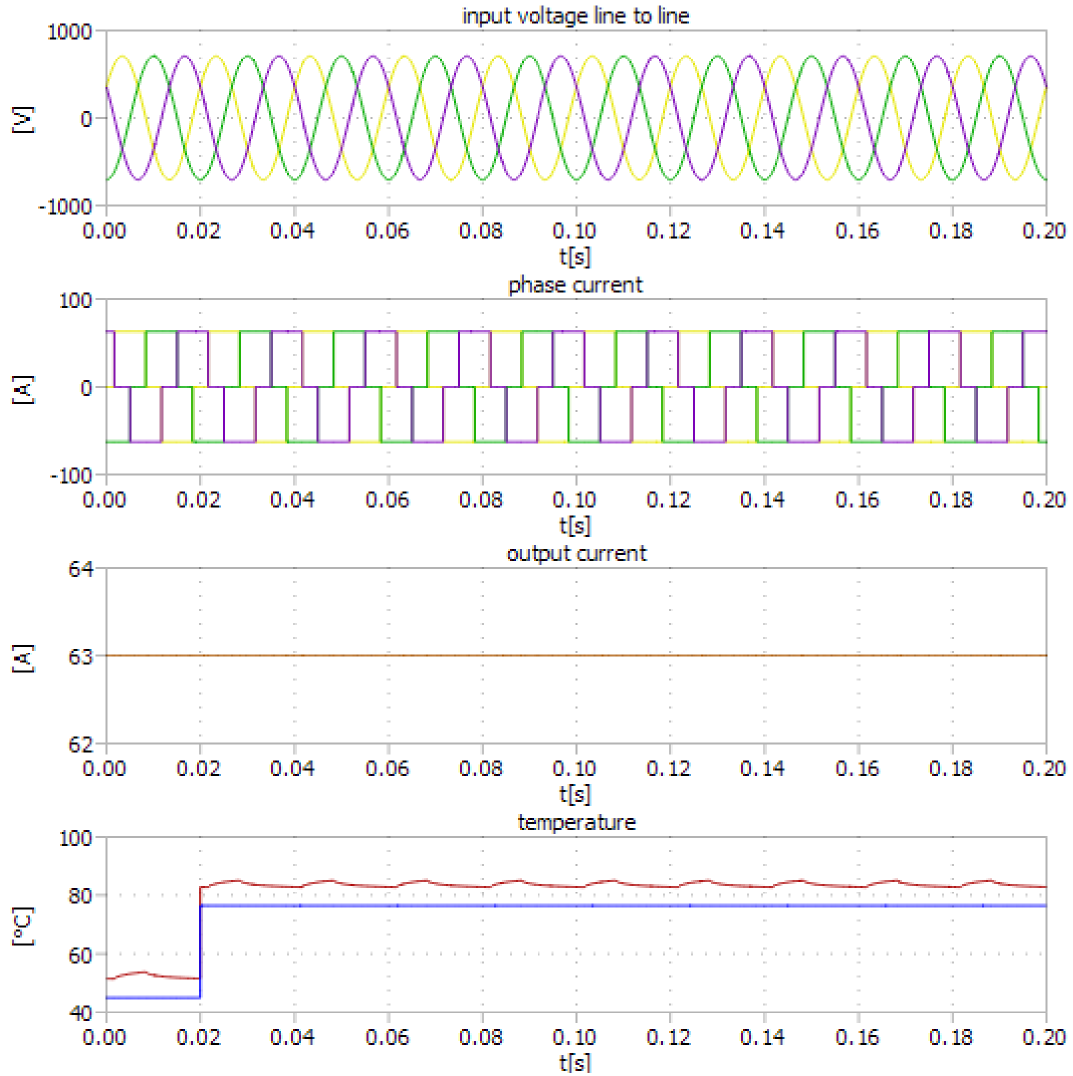

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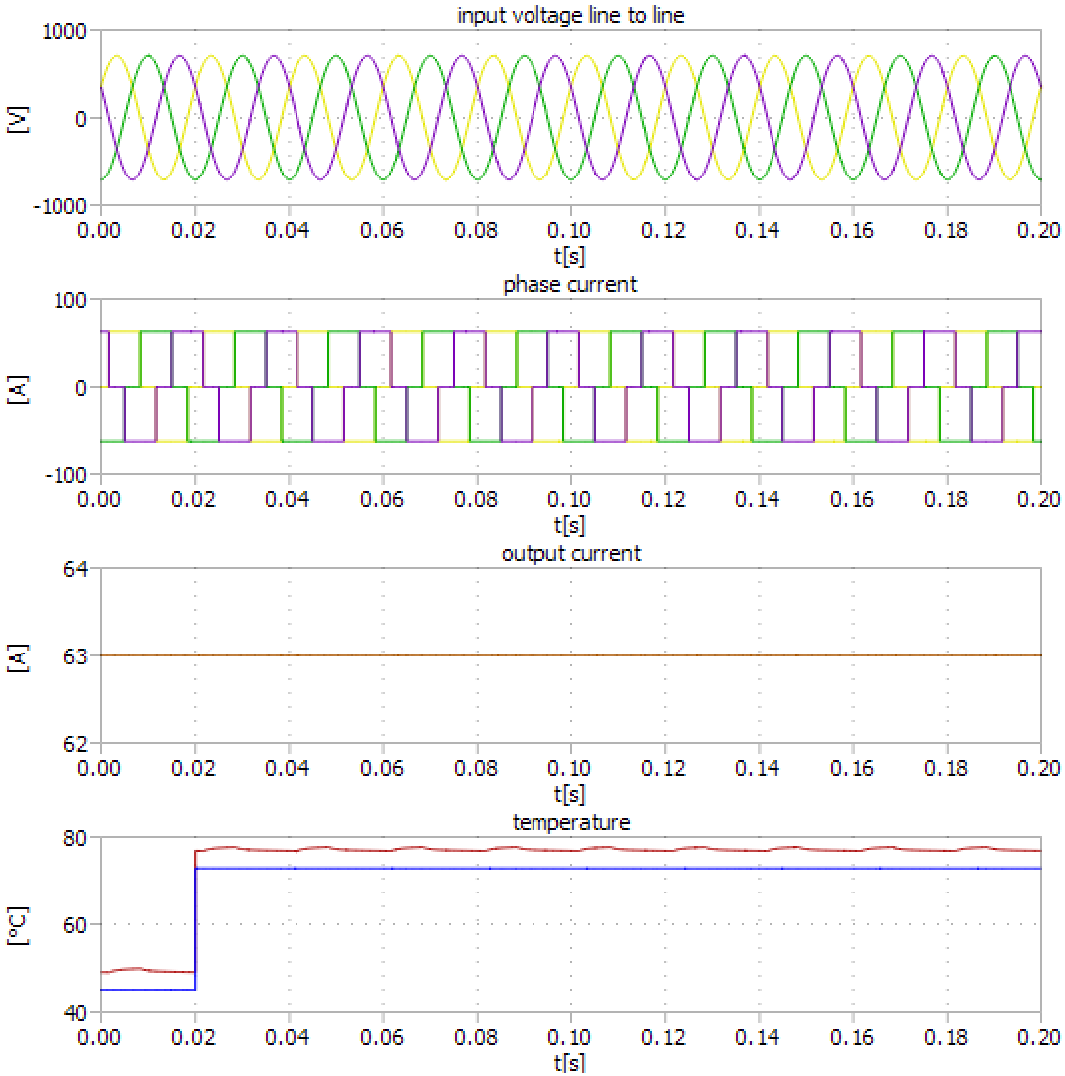

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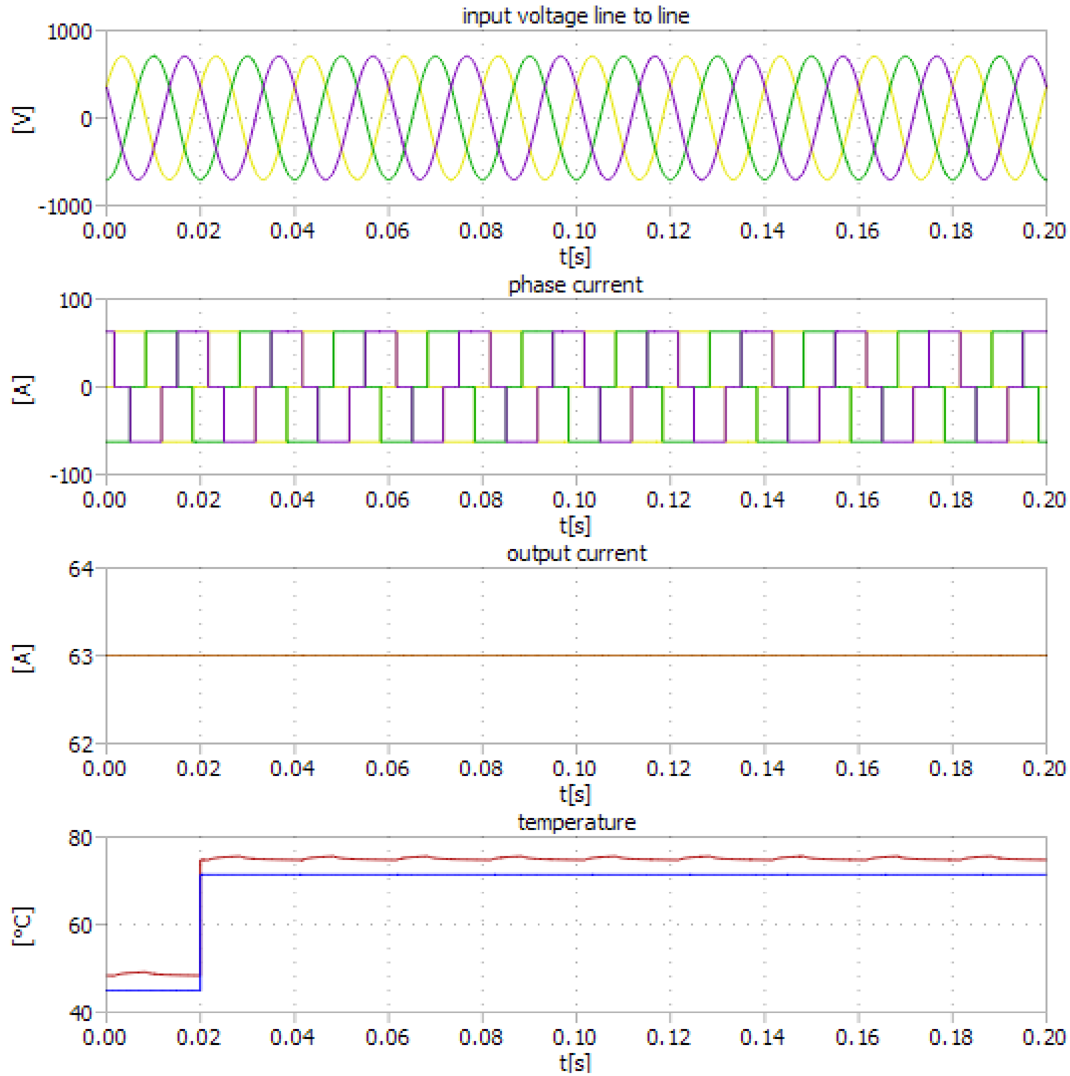

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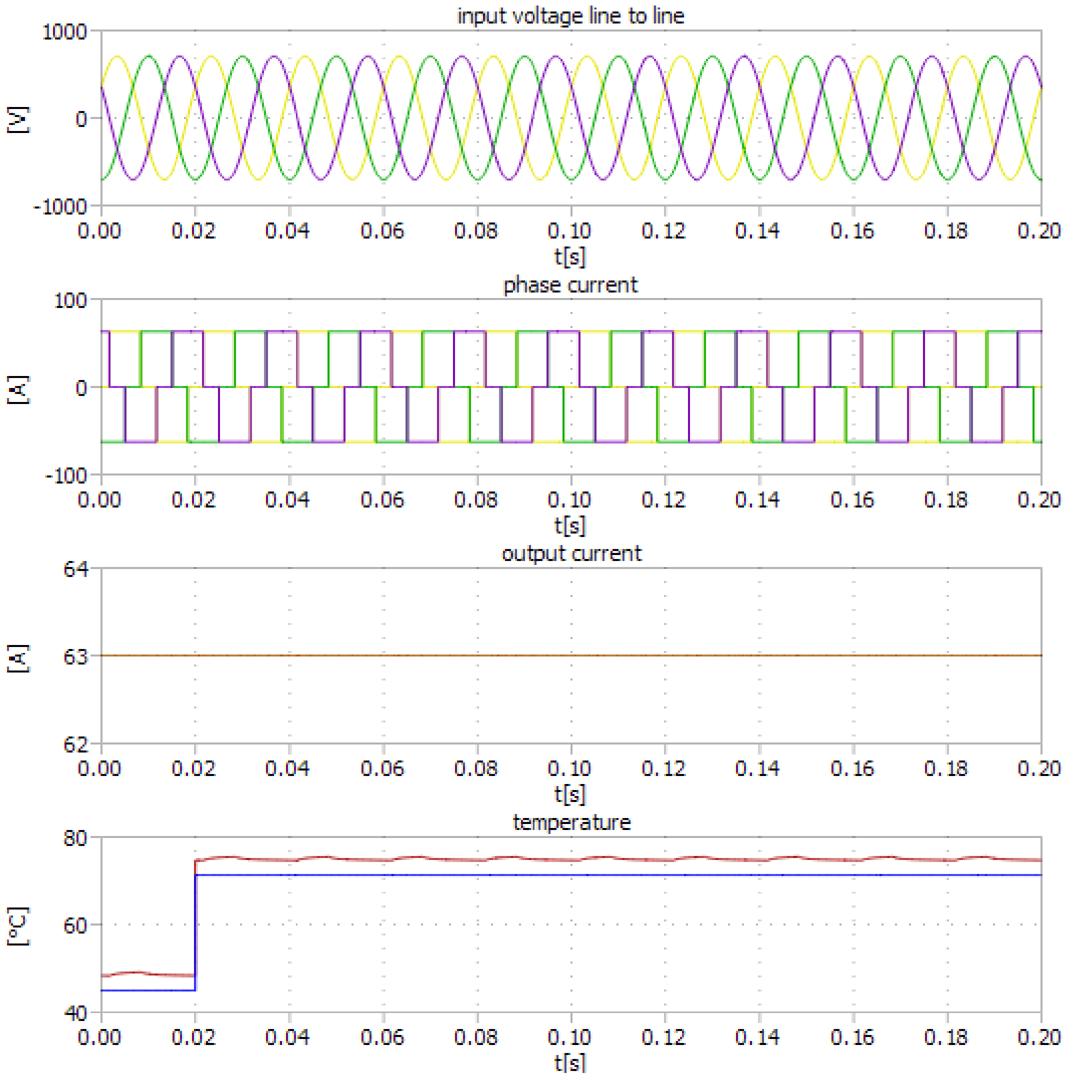

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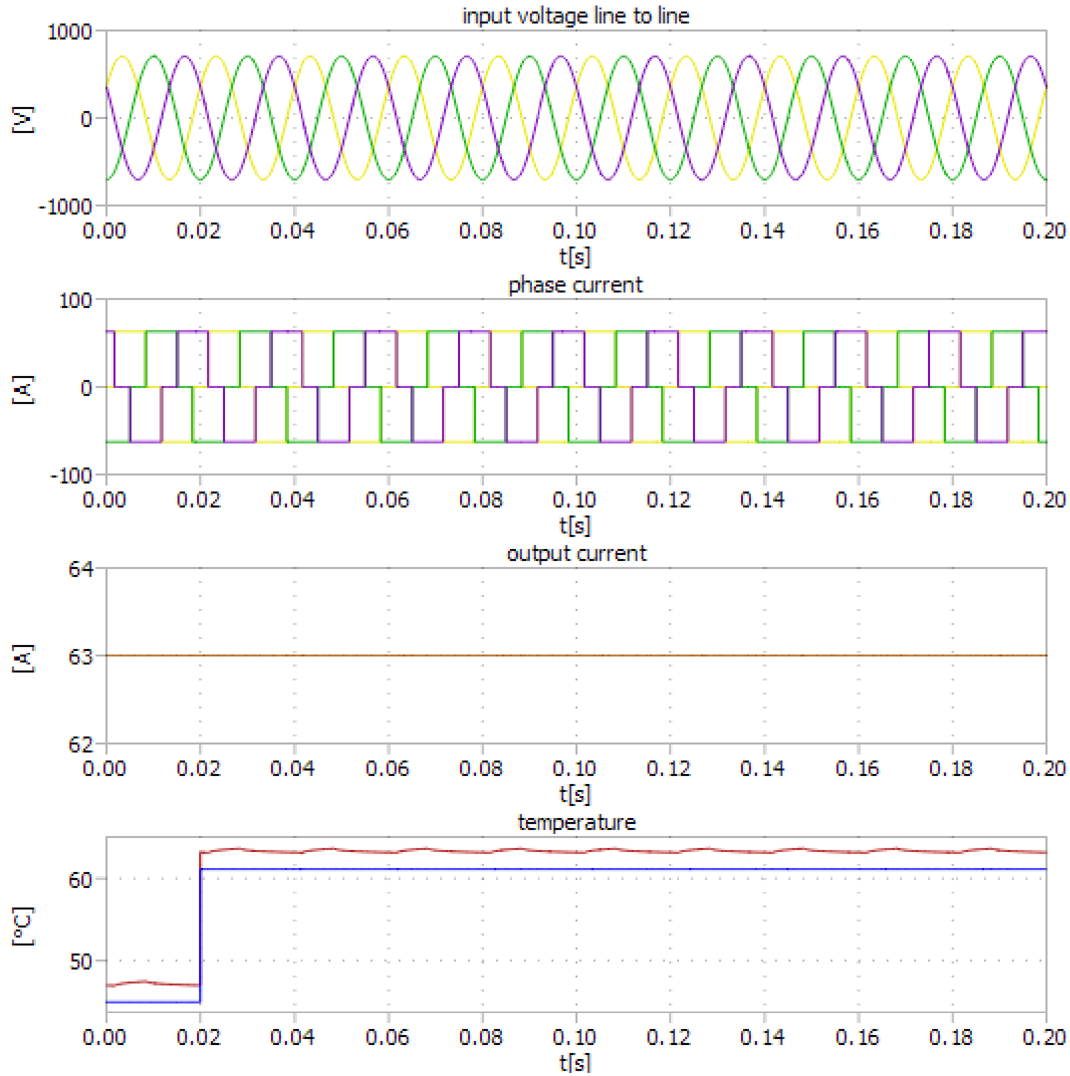

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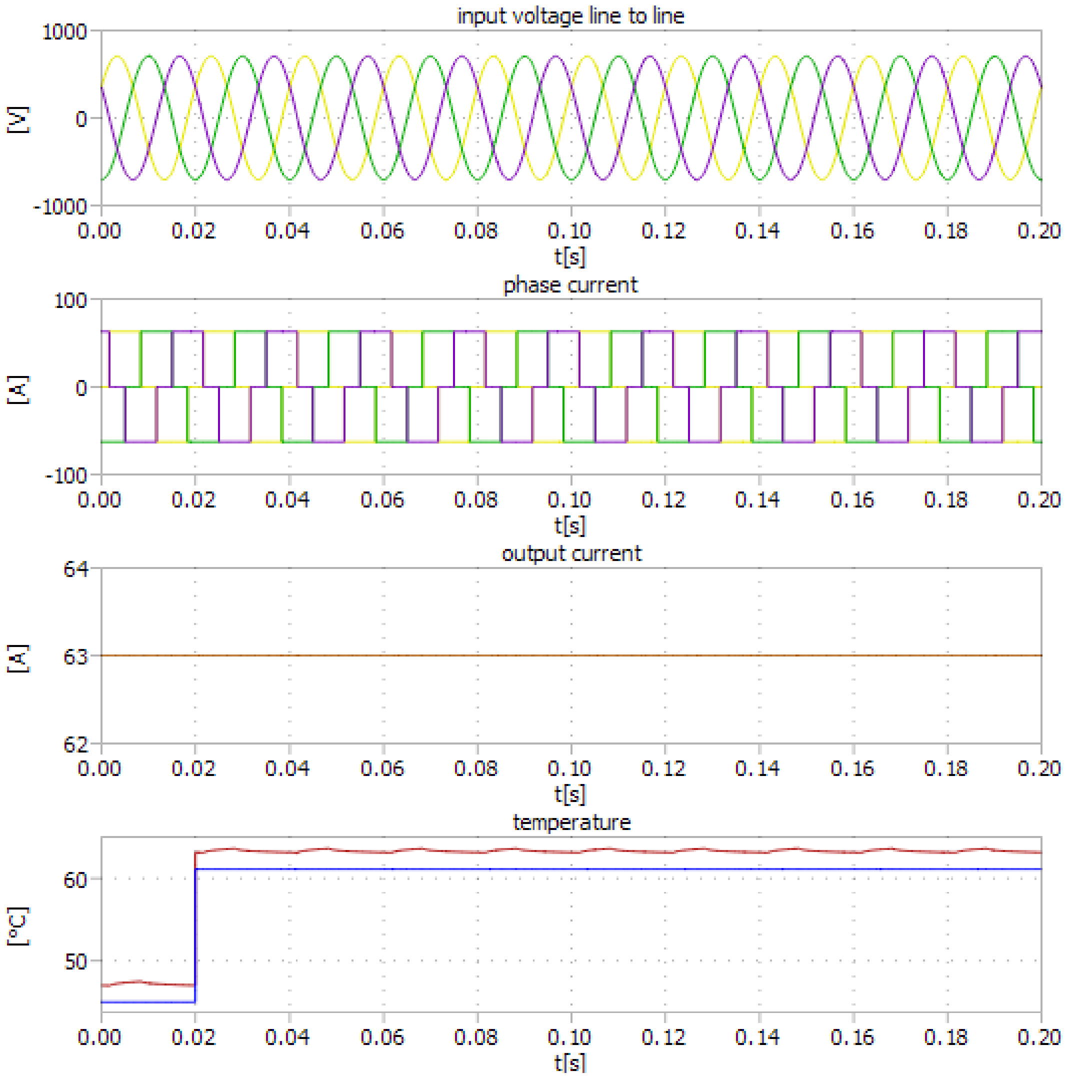

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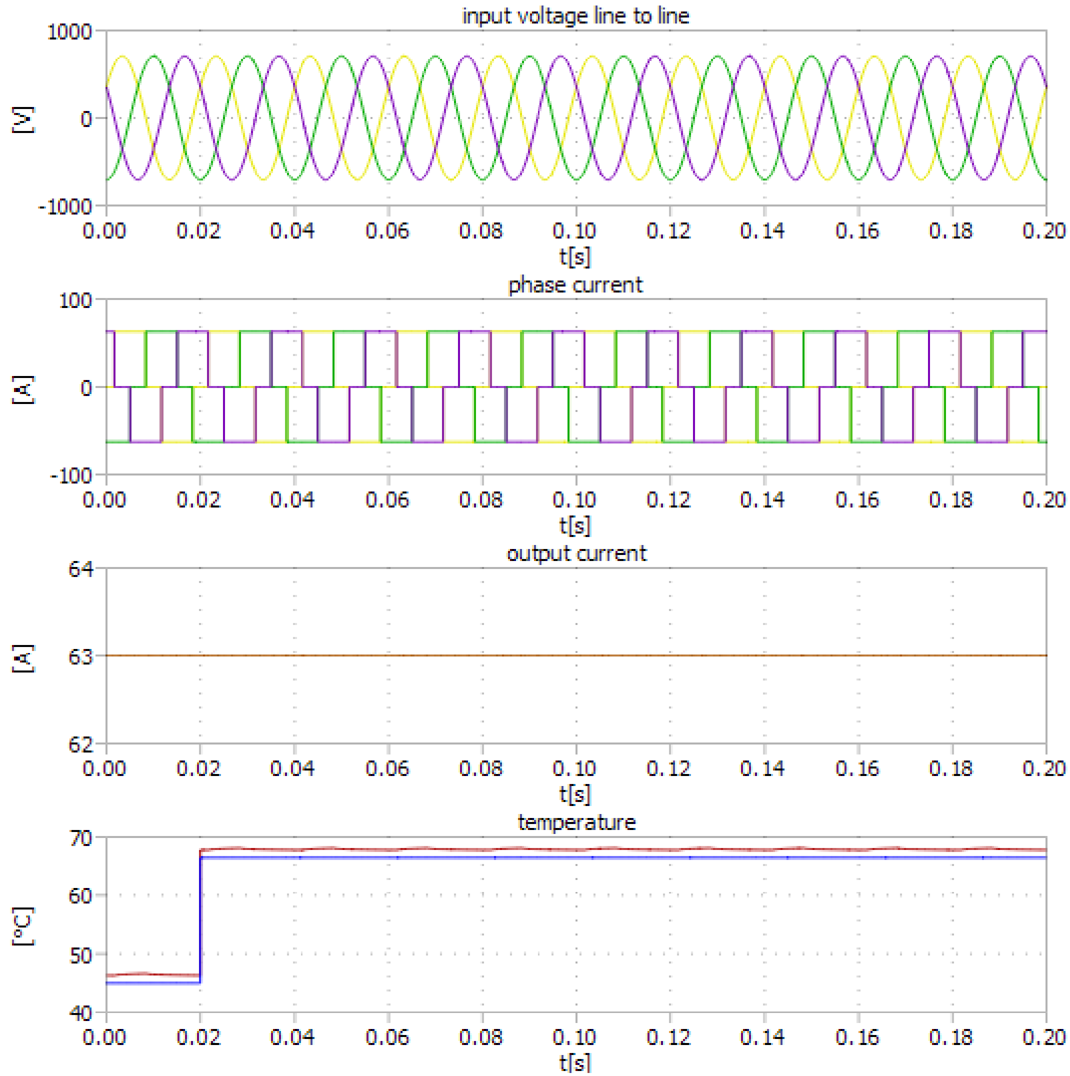
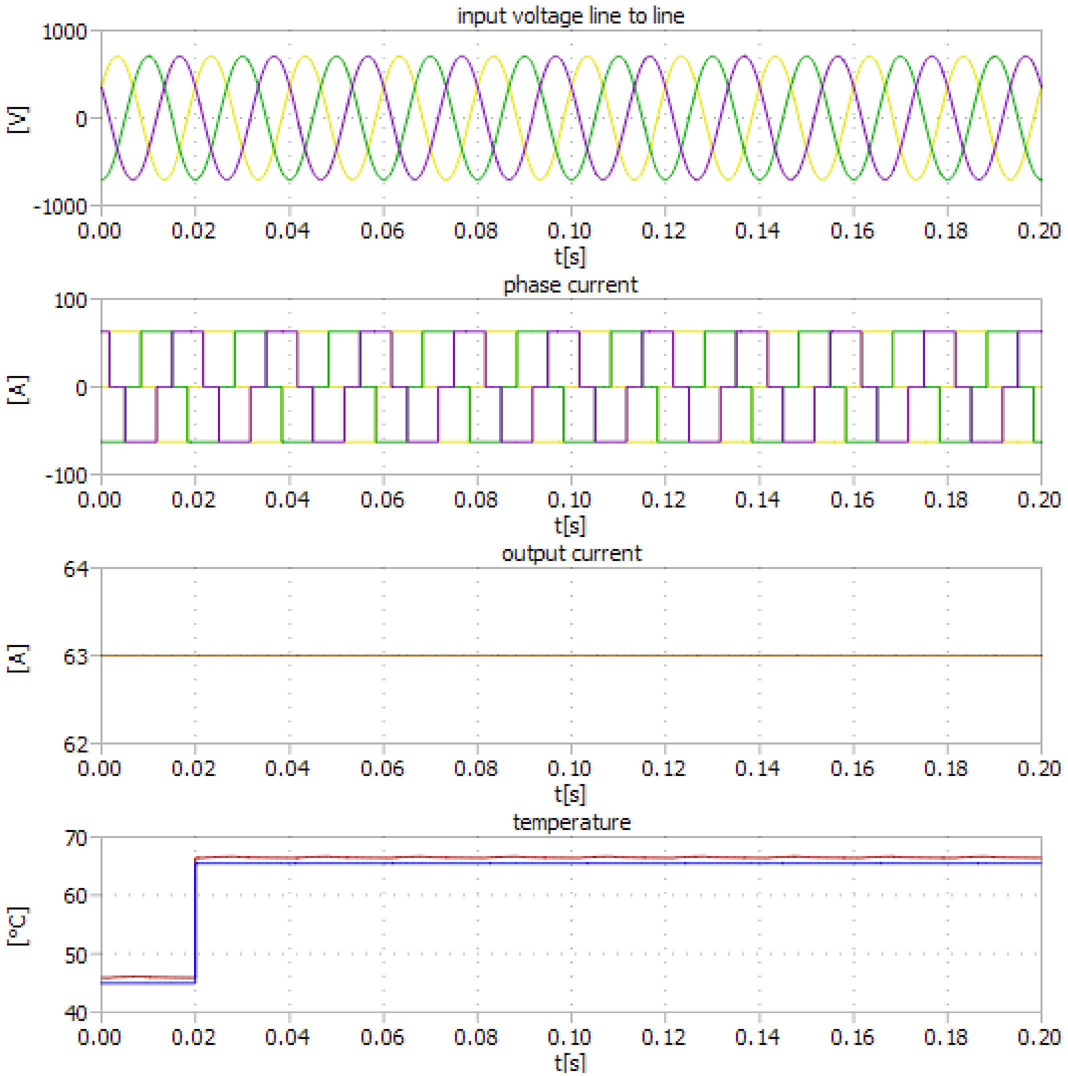


Figure 7.22: B6C - TT425N



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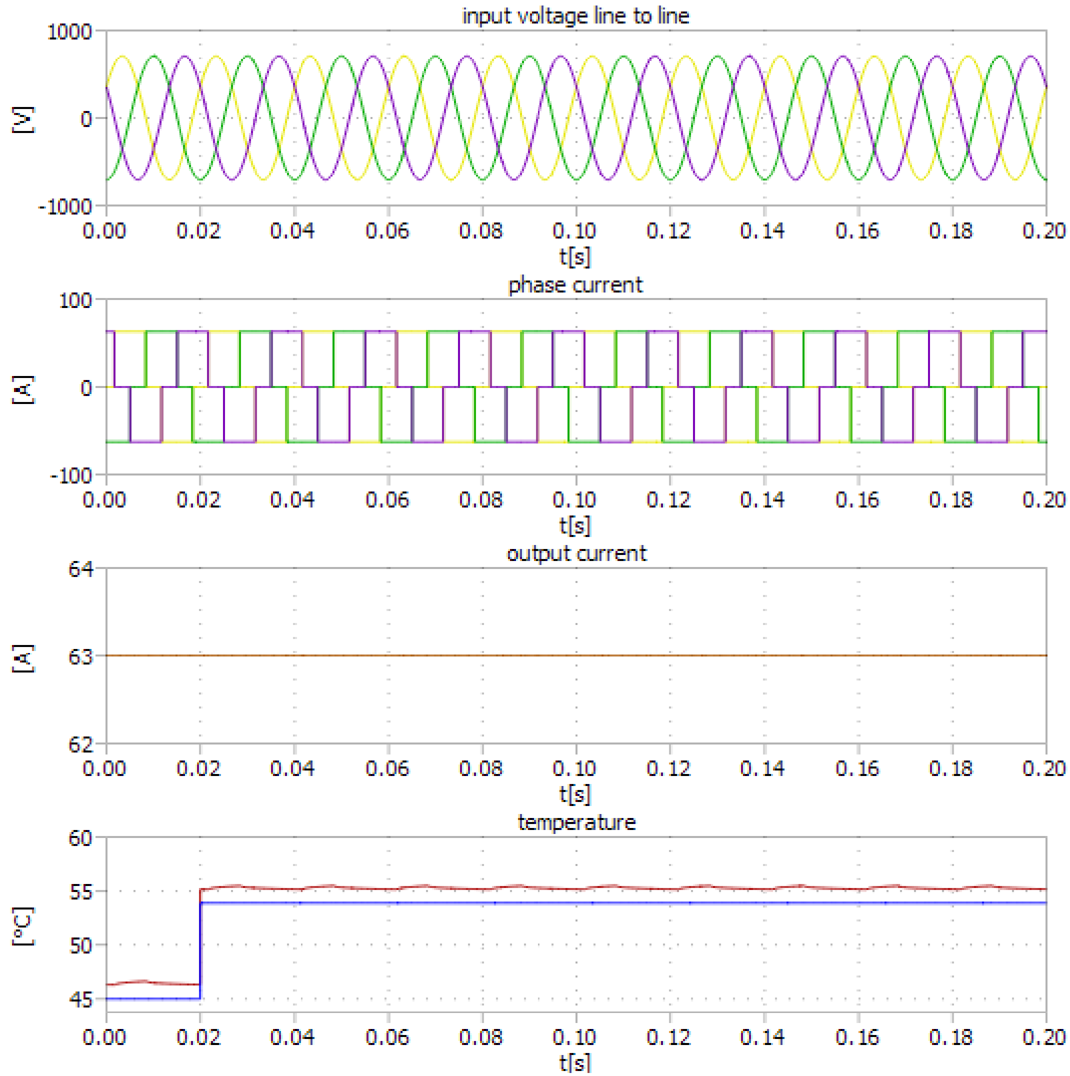
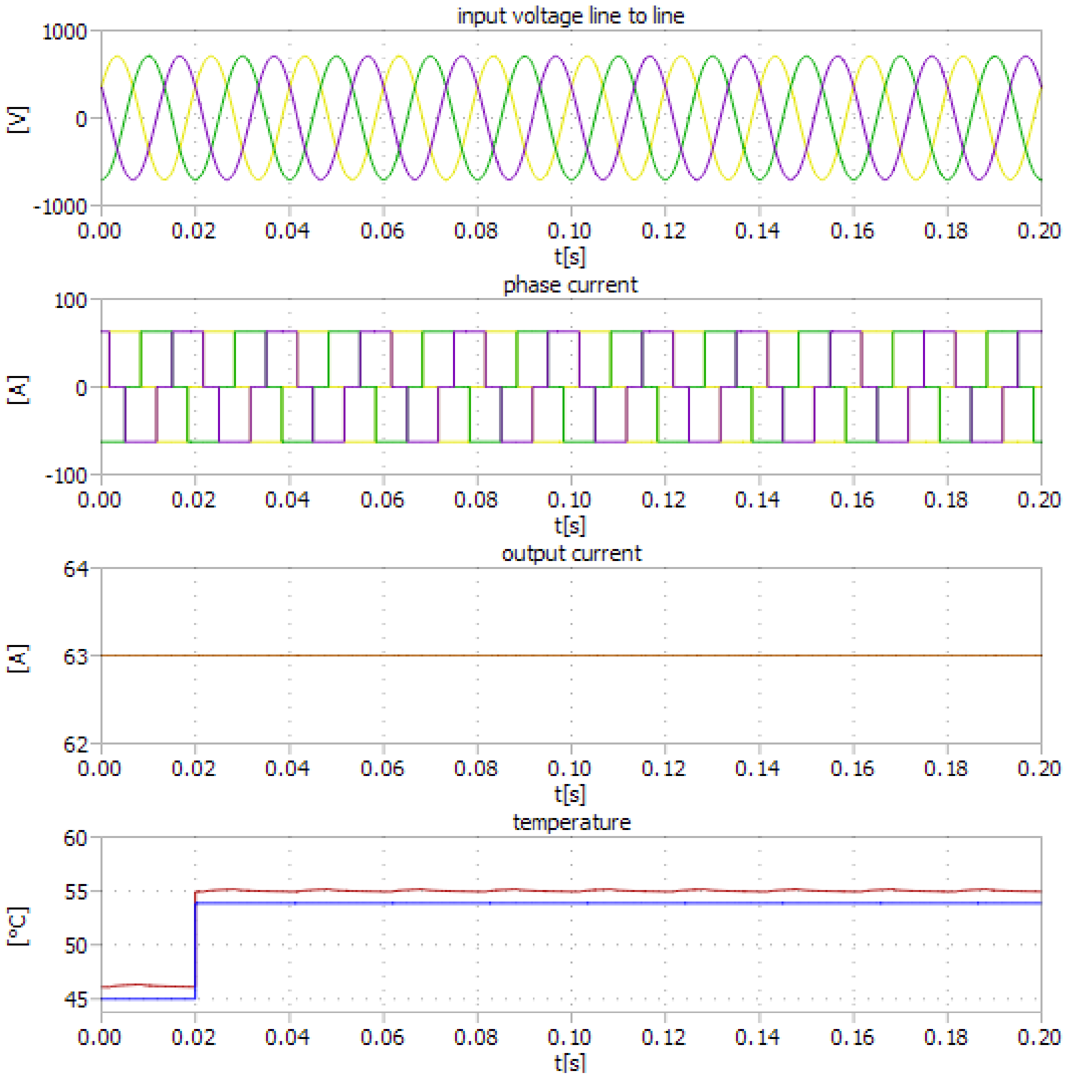


Figure 7.24: B6C - TZ425N



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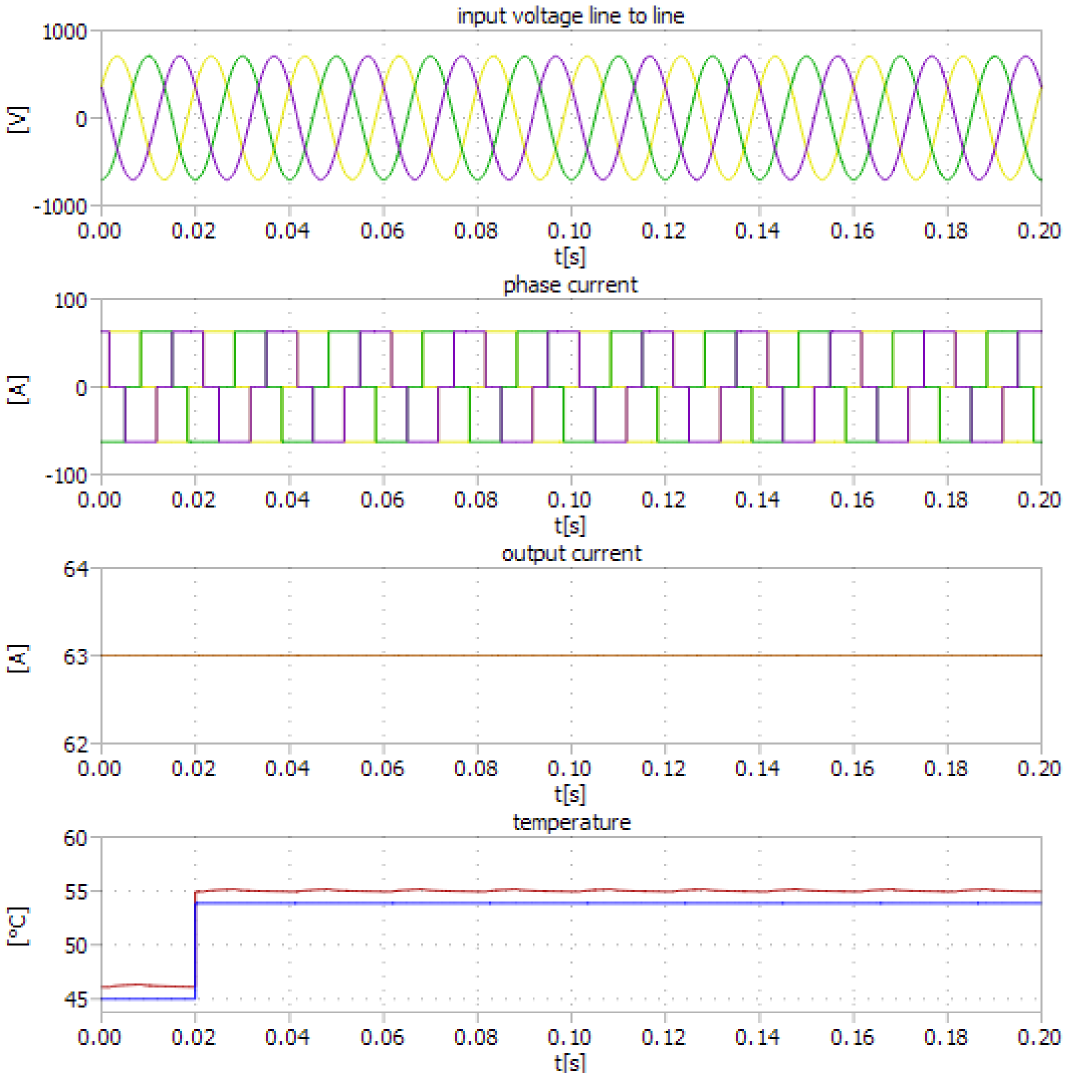

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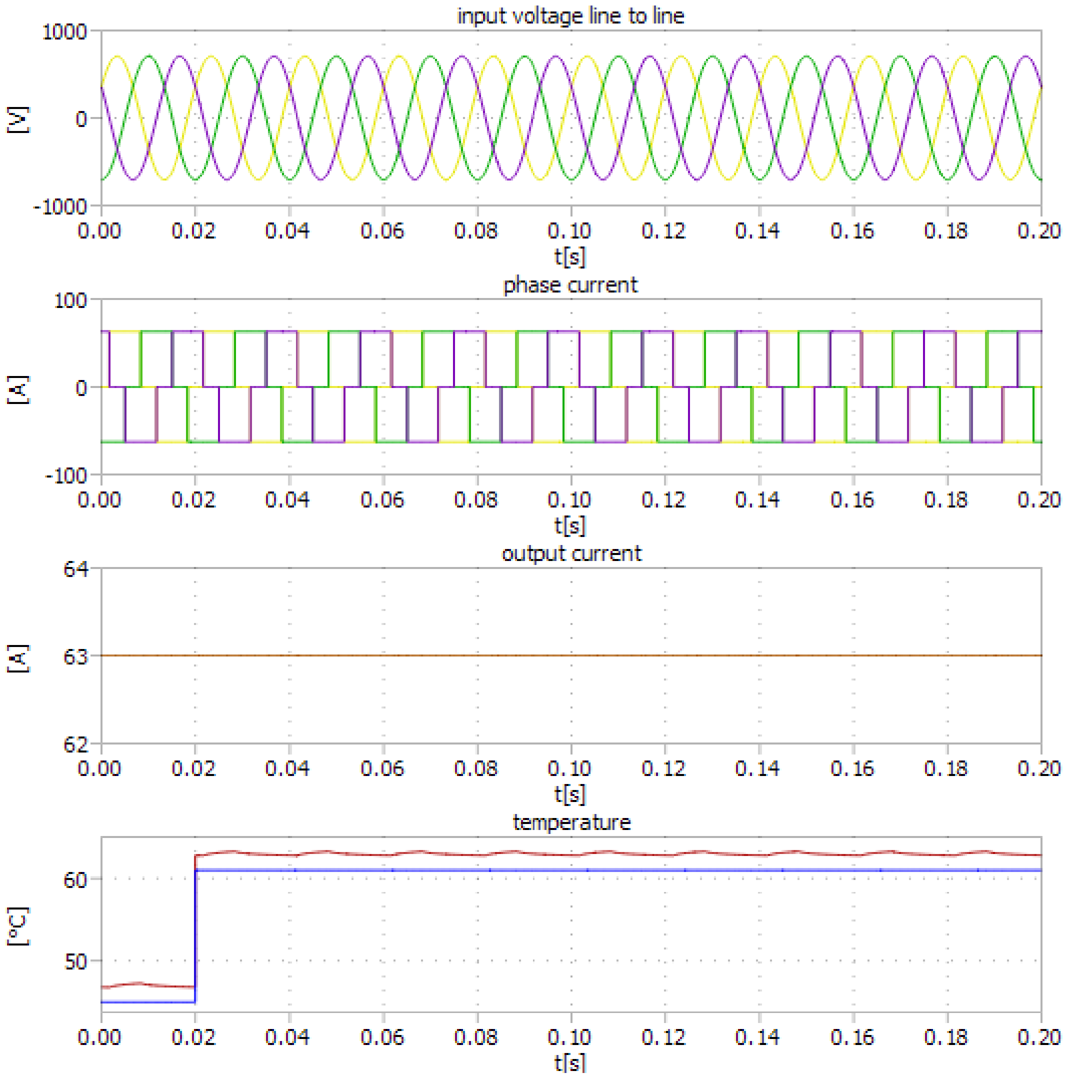


Figure 7.27: B6C - TT270N16KOF

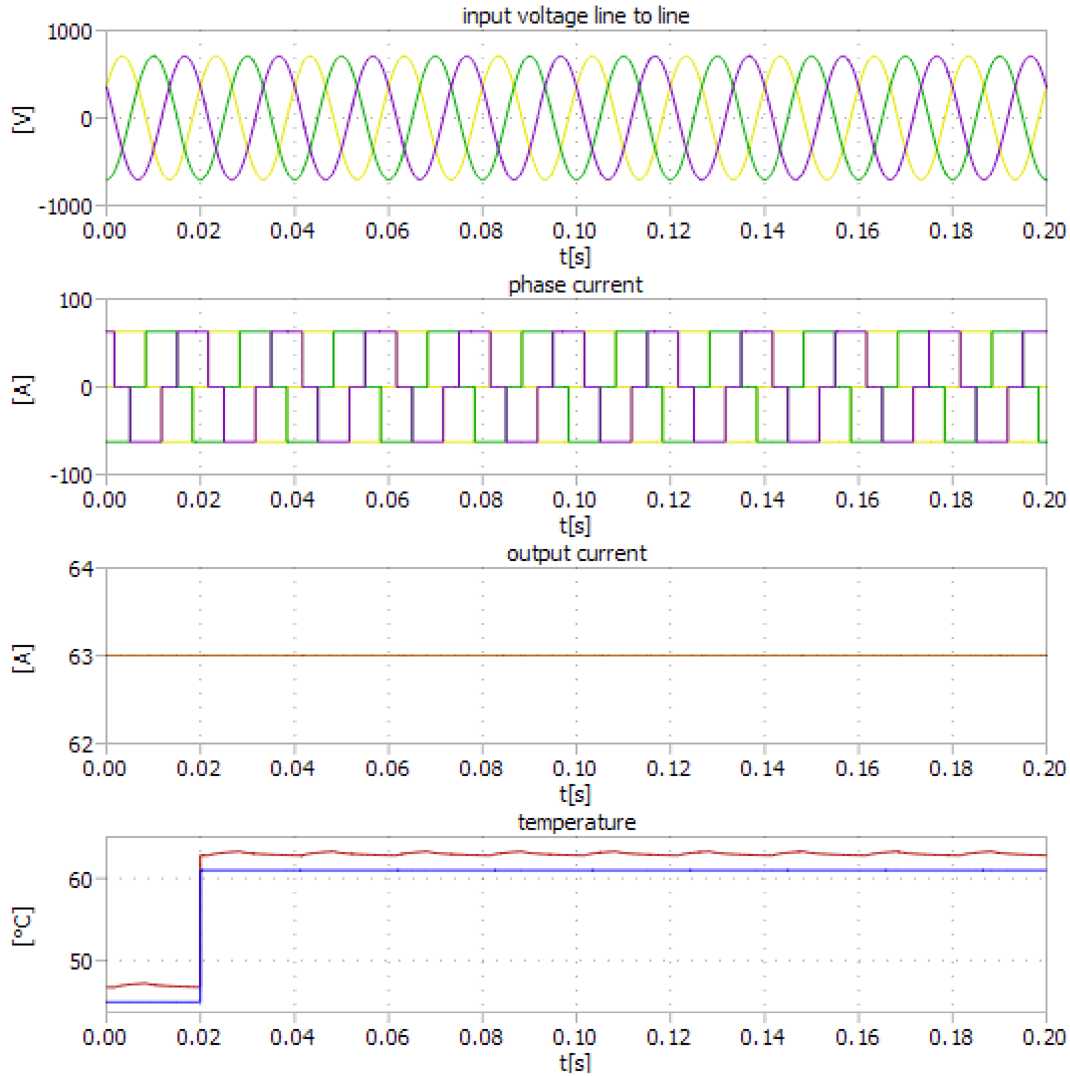


Figure 7.28: B6C - TT330N16AOF

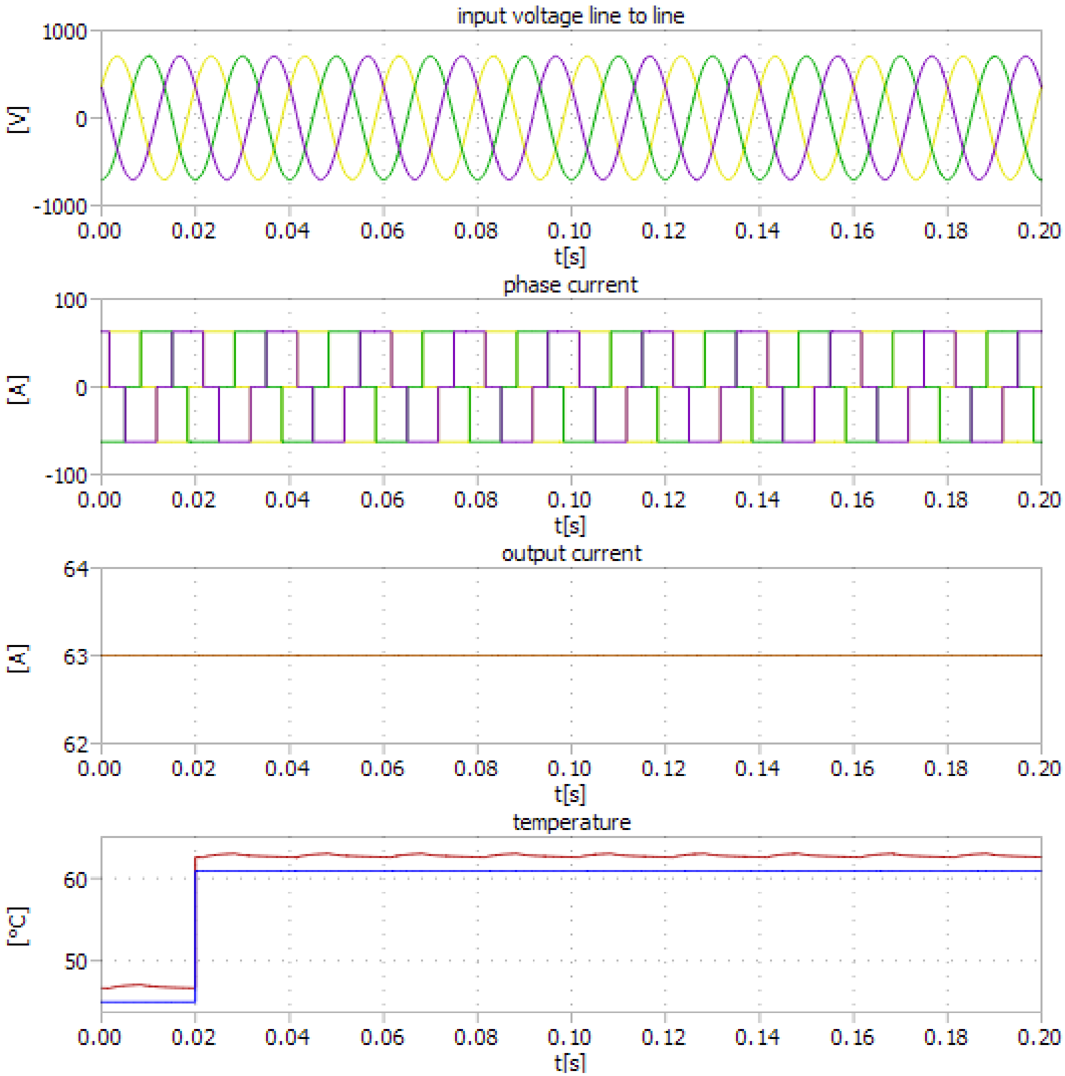
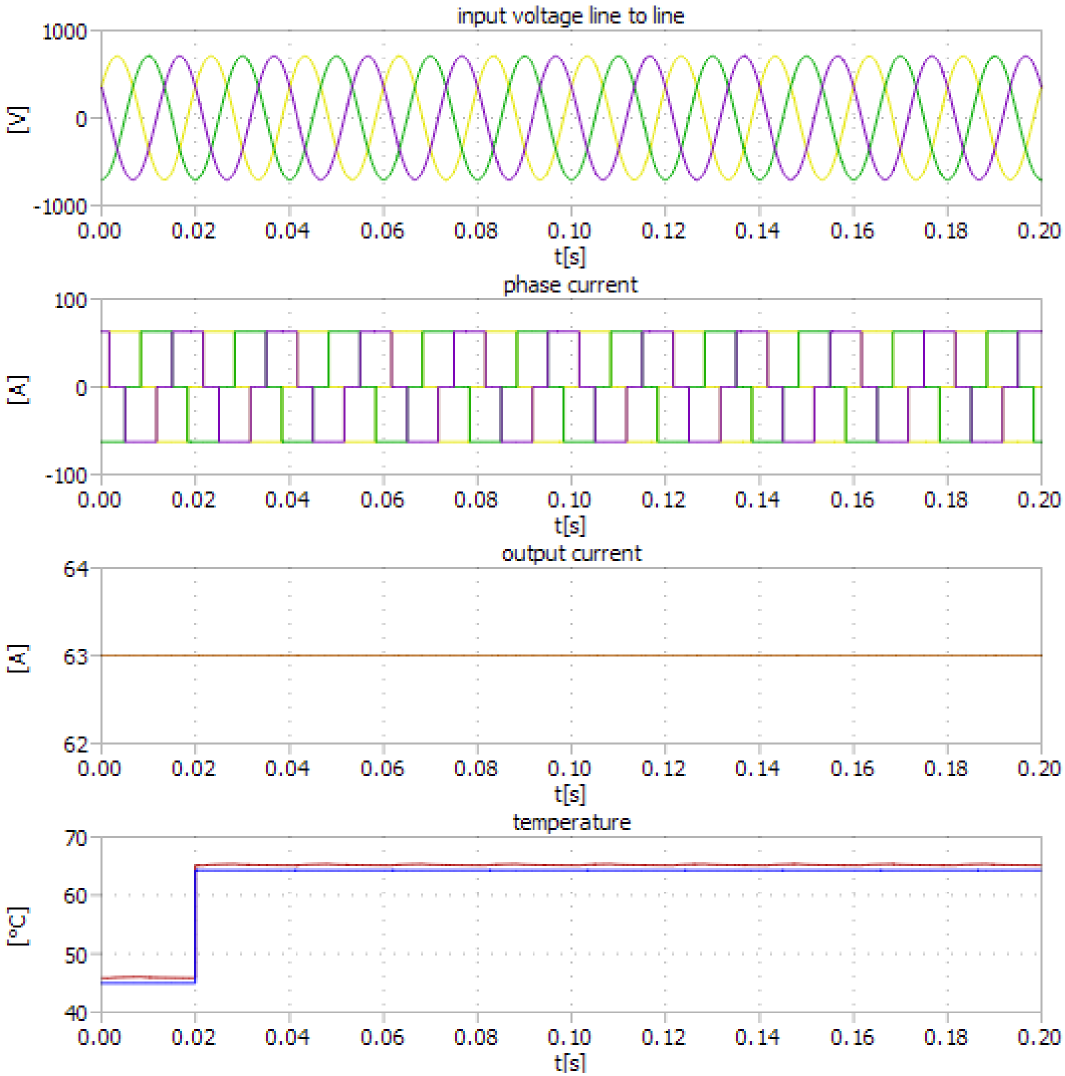


Figure 7.29: B6C - TT330N16KOF



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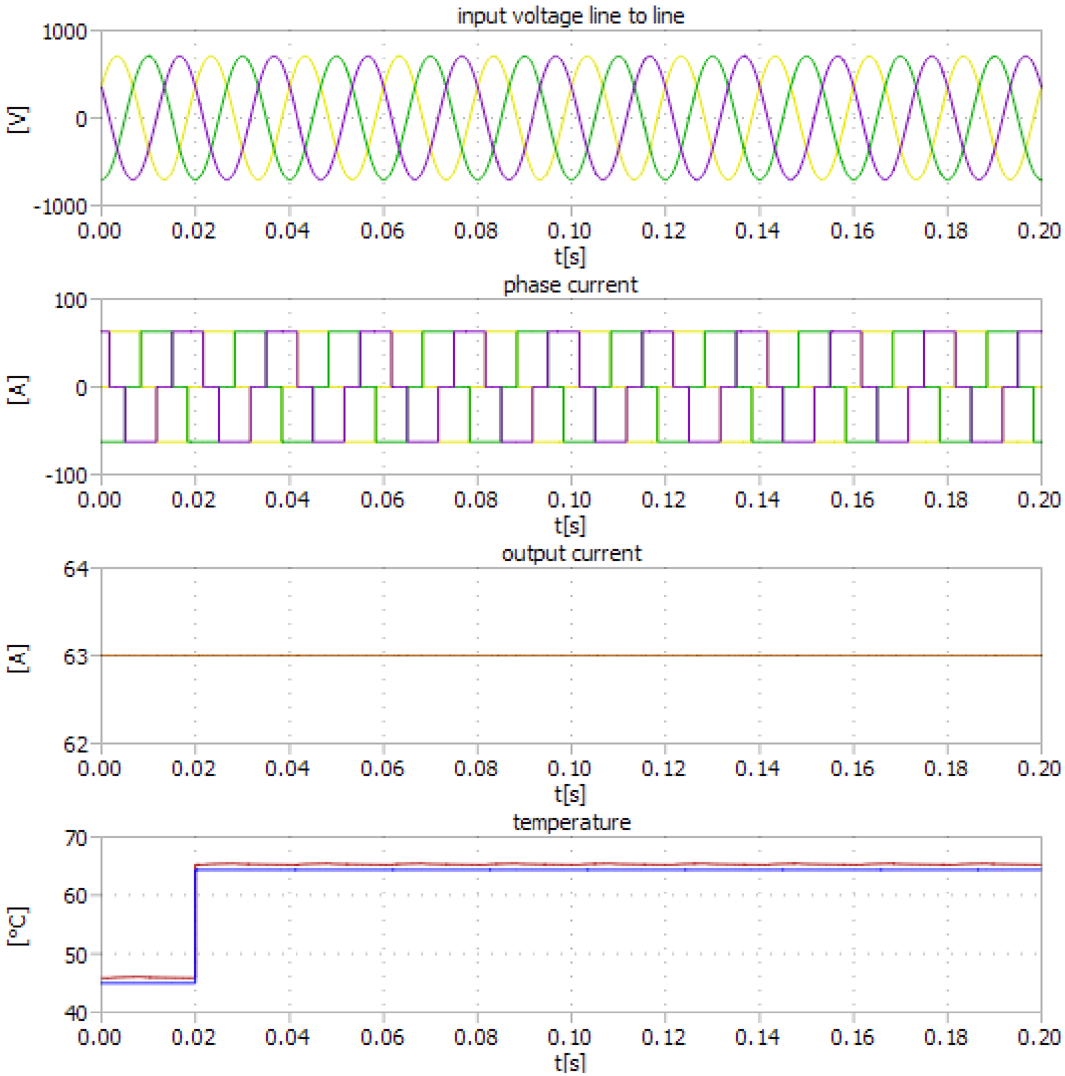

Figure 7.31: B6C - TT570N18KOF

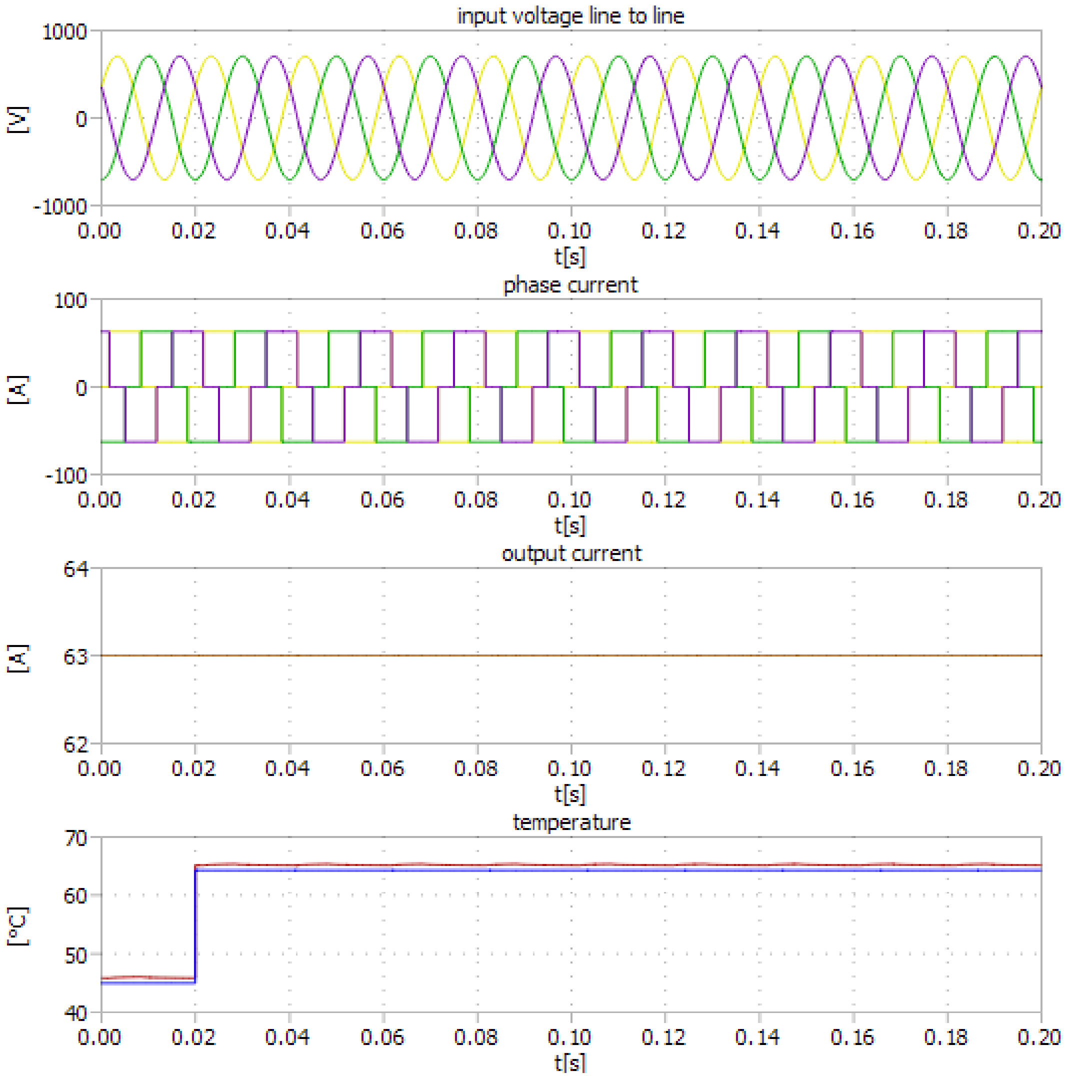

Figure 7.32: B6C - TT600N16KOF

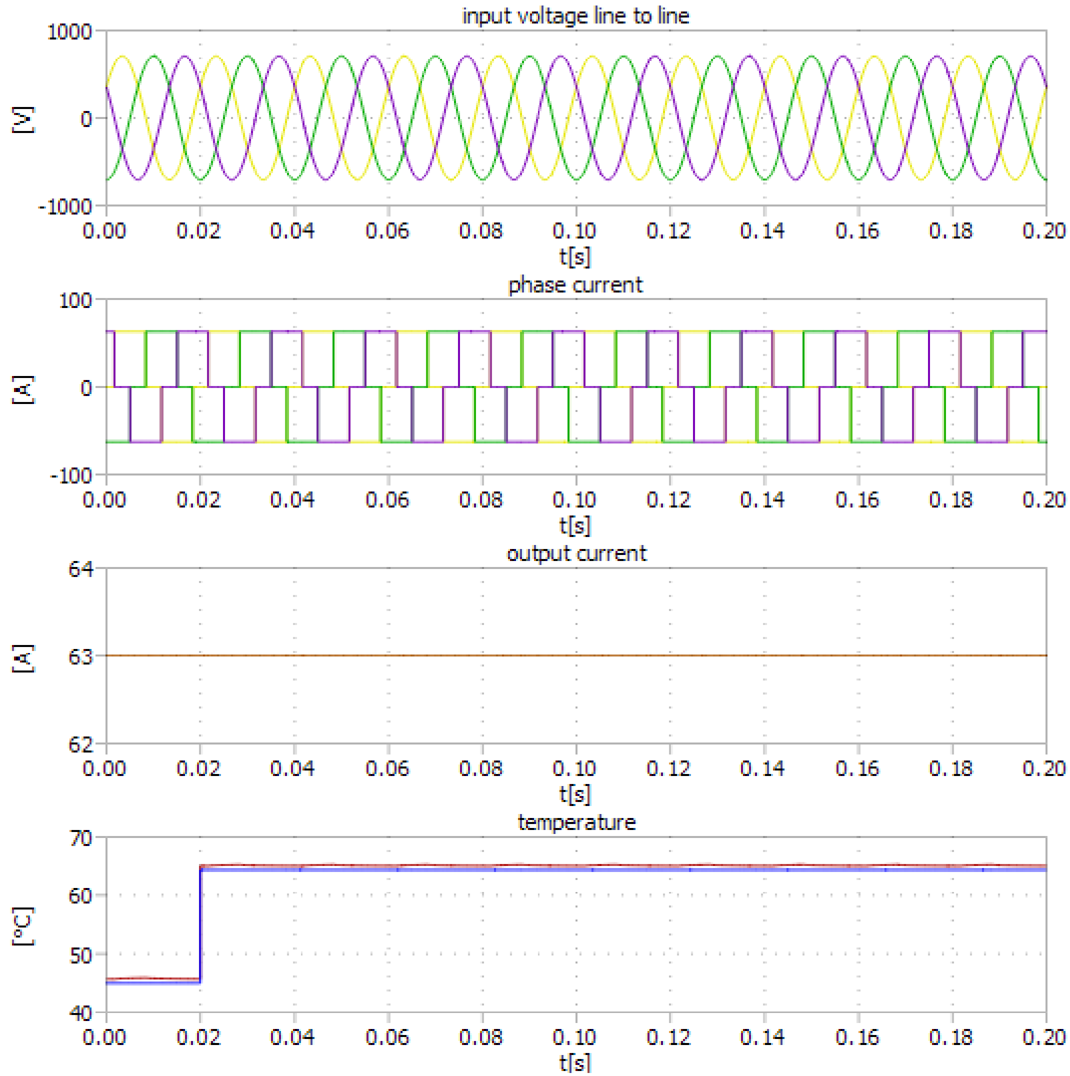

Figure 7.33: B6C - TT780N18KOF

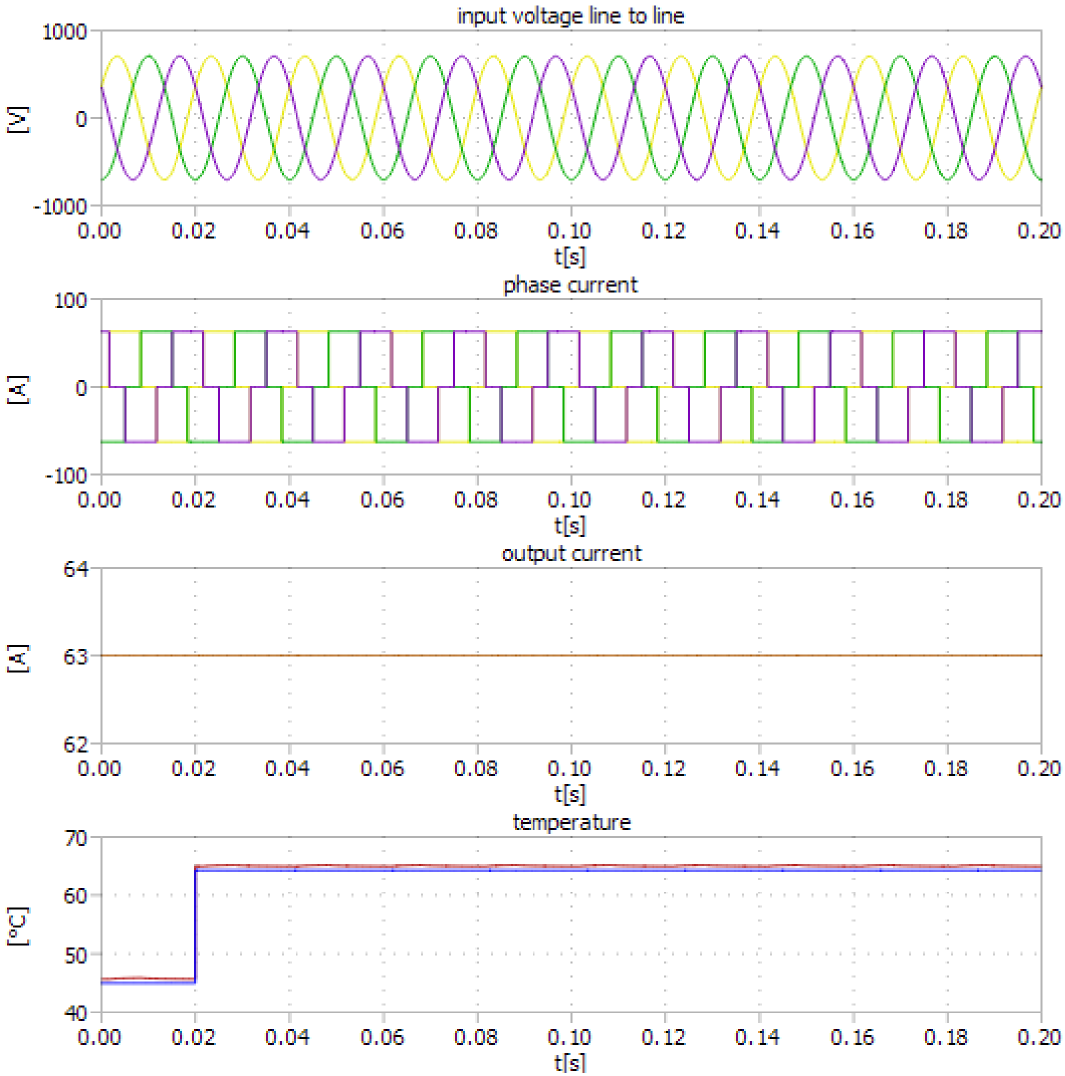

Figure 7.34: B6C - TT820N16KOF

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